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HYDRAULIC MODELLING OF WATER TREATMENT STORAGE TANKS FOR DISINFECTION CONTACT TIME

by

KARA I. HURTIG

©

A Thesis

Submitted to

The Faculty of Graduate Studies and Research in

Partial Fulfilment of the Requirements for the

DEGREE OF
MASTER OF SCIENCE

in

Water Resources Engineering

Department of Civil & Environmental Engineering

Edmonton, Alberta
Fall 2003

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30 September 2003

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Faculty of Graduate Studies and Research

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Abstract

The purpose of this study was to obtain insight into how the design of water treatment storage tanks affects the tank's hydraulic characteristics. The first objective of this study was to verify that physical models are an effective method of evaluating storage tank performance. The second objective was to observe the influence that the internal baffle wall configuration and the tank inlet design has on the hydraulic performance. The results of tracer tests in the models of two storage facilities were found to be comparable to the results of prototype tests. The tracer study data was compared to commonly used techniques for estimating contact time. Insight was attained into the affect of installing pipe diffusers and pipe elbows at the inlet to a storage tank. A general relationship was found between the fluid retention time and the ratio of travel distance to water depth within a tank.

To my family, friends, and classmates who graciously offered me their support, advice and encouragement.

Acknowledgements

I would like to sincerely thank Dr. N. Rajaratnam for his patience, guidance and unlimited encouragement. His enthusiasm and support as my supervisor, throughout my course work and the duration of this study, has been invaluable. I wish to also extend thanks to my co-supervisor Dr. Stephen Stanley for his assistance and insightful advice throughout this study.

I am grateful to Mr. Sheldon Lovell for the design and construction of both physical models and to Mr. Perry Fedun for the assistance and co-operation that he provided throughout the study. In addition, I would like to thank both gentlemen for their friendship and support during my days at the T. Blench Hydraulics Laboratory.

My gratitude also goes to Dr. Ahmed Moawad, who initiated this project and provided its foundation. EPCOR Water Services provided funding and designs for the project as well as information regarding the prototype tanks, and is gratefully acknowledged.

I am thankful for the source of inspiration and advice provided by academic staff and fellow students at the University of Alberta. I am also grateful for the generosity and support provided by the staff of Northwest Hydraulic Consultants throughout the writing phase of this thesis.

Special thanks go to my parents, Dr. Wendy Austin and Mr. Rainer Hurtig and to my brother, Mark Hurtig for the unlimited support, and encouragement throughout many years of academics. In addition, my sincere gratitude and appreciation goes to Peter Onyshko for his friendship, assistance and moral support throughout my course work and thesis preparation.

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List of Symbols

a	acceleration
AEP	Alberta Environmental Protection
A_m	area in the model
A_p	area in the prototype
ASCE	American Society of Civil Engineers
AWWA	American Water Works Association
a, b	regression coefficients
C	tracer concentration at time t
C/C_0	tracer concentration divided by initial tracer concentration
C_0	initial concentration of tracer solution
C_{back}	background concentration
CE#	E.L. Smith configuration number
CR#	Rossdale configuration number
CSTR	continuously stirred tank reactors
C_t	disinfectant concentration (mg/L)
CT	disinfectant concentration multiplied by the amount of time the water is in contact with the disinfectant
DBP	disinfection by-products
D/DBPR	Disinfectant / Disinfection By-Product Rule
E#	E.L. Smith experiment number
F_i	force of inertia
F_g	force of gravity
F_r	Froude number
F_{rm}	force of gravity in the model
F_{rp}	force of gravity in the prototype
g	acceleration of gravity
g_m	acceleration of gravity in the model
g_p	acceleration of gravity in the prototype
IESWTR	Interim Enhanced Surface Water Treatment Rule

k	rate constant of inactivation
k'	rate constant of lethality
L	a characteristic length
λ	length scale, L_p/L_m
$level_C$	sensitivity range for the time dependent concentration
$level_{back}$	sensitivity range for the background concentration
L/min	litres per minute
L_m	characteristic length in the model
L_p	characteristic length in the prototype
L:W	ratio of the length of travel to the channel width
L:D	travel distance from the tank inlet to the outlet divided by the water depth within the tank
m	dead space fraction of tank volume
M	mass
1-m	effective fraction of tank volume
m	metre
m^2/s	square metres per second
mg/L	milligrams per litre
min	minutes
ml	millilitre
ML/d	megalitres/day
mm	millimetre
mm^2	square millimeters
n	coefficient of dilution
N	concentration of viable microorganisms
N_0	number of viable microorganisms at time 0
N_t	number of viable microorganisms at time t
nm	nanometer
p	plug flow fraction of the effective part
1-p	perfect mixing fraction of the effective part
ρ	density

PFR	plug flow reactor
pH	negative logarithm of the effective hydrogen-ion concentration
ppb	parts per billion
Q	discharge
Q_m	discharge in the model
Q_p	discharge in the prototype
Q_S	system discharge
Q_T	tracer study discharge
R_e	Reynolds number
R#	Rossdale experiment number
RTD	residence time distribution
SDWA	Safe Drinking Water Act
SWTR	Surface Water Treatment Rule
t	time (minutes)
θ	t/T_d, time divided by theoretical detention time
T_d	theoretical detention time
t_i	initial indication of tracer in the effluent
T_m	time in the model
T_{90}/T_{10}	Morril index
T_p	time in the prototype
T_{10}	effective detention time
T_{10}/T_d	baffle parameter, effective detention time divided by theoretical detention time
T_{10S}	T_{10} at system discharge
T_{10T}	T_{10} at tracer discharge
THMs	trihalomethanes
U	velocity of flow
U_m	velocity of flow in the model
U_p	velocity of flow in the model
µg/L	microgram per litre

USEPA	United States Environmental Protection Agency
UV	ultraviolet radiation
V	volume of the tank
V_m	volume in the model
V_p	volume in the prototype
ν	kinematic viscosity
WTP	water treatment plant

1.0 Introduction

1.1 General

In the past two decades, growing concern over microbiological contamination of drinking water has made increasingly more stringent requirements for water treatment processes necessary. Disease caused by microbiological contaminants has been labelled by the United States Environmental Protection Agency (USEPA) as today's greatest preventable health risk. Outbreaks of waterborne disease are continuing to occur at high levels in all parts of the world. The consequences of improper treatment can be devastating. In 1991, insufficient disinfection of the drinking water supply in Peru contributed to a cholera epidemic that infected a population of more than 300,000 (Anderson 1991). Of these people over 3,500 died of their infections. In May 2000, E. Coli contamination and improper treatment of the drinking water supply in Walkerton, Canada led to the deaths of 7 people and to the illness of 2,300 others.

In recent years, population growth and ageing infrastructure have put an increasing strain on existent water distribution systems. This, in turn, has heightened the importance of the removal and/or inactivation of cysts and viruses found in drinking water. In North America, water treatment regulations and advances are highly influenced by the USEPA. In 1989, the USEPA introduced important new requirements with regards to water quality. These new standards are included under what is commonly known as the Surface Water Treatment Rule, SWTR. The SWTR introduced a value known as CT. CT is defined as the disinfectant concentration in the water multiplied by the amount of time the water is in contact with the disinfectant. Under the SWTR, CT is used to determine whether or not the stringent requirements for inactivation of microorganisms and viruses are being achieved.

Storage tanks in water distribution systems are an integral part of the water treatment process. These large basins provide storage for drinking water, which is needed to satisfy population demands, fire-fighting needs, and industry requirements. If properly designed, these tanks can also contribute greatly to the disinfection process as disinfectant contact basins. As water circulates through the tanks, it can enable mixing and proper contact time with the chemicals added for disinfection. Storage reservoirs are an ideal venue for disinfection, because the immense tanks can provide for prolonged contact periods, and the addition of disinfectant near the end of the treatment process may also provide significant benefits. Contemporary methods, used in the treatment of drinking water, encourage disinfectant application in the later phases of the treatment process to help reduce the formation of disinfection by-products (National Health and Welfare 1993). However, the locations of disinfection addition in the water treatment process can vary depending on the process and the facility. The later addition of disinfectant may also facilitate maintenance of the disinfectant residual required at the entrance to the distribution system. Since storage tanks are already an integral part of the water treatment process, designing or modifying the internal arrangement of these tanks to promote a dual function as a contact chamber, can be a relatively inexpensive method for improving the quality of the treated water.

Storage basins do not naturally exhibit the ideal hydraulic characteristics of a disinfectant contact chamber. Modifications to the internal geometry of a storage tank can have a significant impact on its hydraulic efficiency, more specifically its abilities to provide adequate mixing and retention time. Popular installations used for improving the hydraulic performance are baffle walls, and inlet or outlet modifications such as weirs, baffles and diffusers. Operational variables such as water depth, water temperature, and flow rate may also influence the contact hydraulics of the reservoirs.

Flow characteristics within distribution storage tanks are complex. The flow first enters the tank as a turbulent jet, which is continuously redirected as the jet impinges on the walls within the tank. The flow pattern is further complicated by the circulation of flow existing between the inlet and the outlet, and by the stagnant areas within the tank's reserve. The flow within these basins and around their internal baffle configuration is complex and researchers have not yet standardised a consistently reliable and cost-effective method for designing and testing these systems. More data is needed to supplement and solidify general trends developed by research to date.

1.2 Storage Tank Performance Evaluation Techniques

Hydraulic systems such as storage tanks may be affected by many factors and therefore caution must be exercised when choosing a method of analysis. Hydraulic processes may be examined using a number of different methods. They can be assessed theoretically by using analytical solutions or numerical models, or experimentally through physical models or field data. It is important to determine which of these methods will produce the most accurate measurement of performance with regards to distribution storage tanks.

The application of theoretical methods can provide inexpensive and reliable solutions to simple hydraulic problems. However, as the flow system becomes more complex, it becomes more difficult to apply theoretical calculations. For example, a turbulent jet entering a distribution tank provides good mixing and its velocity provides momentum for it to circulate through a basin, but it is a complicated flow pattern to study and predict. It is not possible to solve the Reynolds equations, which represent turbulent flow in a theoretical manner. There exists a so-called 'closure problem' and it would require a number of self-consistent assumptions to solve the equations. For simpler turbulent jet flows, one could make some boundary layer type of assumptions, but for turbulent jets moving through a shallow tank with several baffles, it would be very difficult to

make suitable assumptions. Methods like the k-e model (Launder and Spalding, 1972; Rodi, 1980) could be tried with perhaps additional adjustments to account for the effects of the baffles and their circulation regions. Calculations in this case would likely be tedious and complex and would require validation through experimental testing. There are also a class of simplified models developed by environmental engineers such as: the Plug Flow Reactors (PFR) and Continuously Stirred Tank Reactors (CSTR). These models are not suitable to describe the details of the flow pattern produced by complex baffle systems. They are simple estimates based on ideal flows.

Experimental examination of a hydraulic system can be performed through observation of the full-scale system or through investigation of a small-scale model of the system. Data collected from examination of the full-scale tank or prototype can offer the most accurate description of the system under investigation, but it can also be costly and impractical. For this type of study, altering the baffling arrangement in a full-scale distribution tank is unreasonable because of the cost of material, labour, and time. It is important to note that many of these systems cannot be taken off-line for an extended period of time. Knowledge concerning the flow in these tanks is recommended prior to the construction phase.

The use of scale models and basic experiments with various design alternatives is the most prudent method of attaining insight into the hydraulic processes, which occur within this type of hydraulic system. A downscaled version of the system is more adaptable and much less expensive to work with than the prototype. Physical modelling is a widely accepted method for studying the design and operation of many types of hydraulic structures. If the proper design criteria are applied to the construction of a model, it is feasible for that model to reproduce many traits of a complicated flow process that is connected with the prototype. It is for this reason

that hydraulic modelling has been adopted in this study as the preferred method for investigating contact hydraulics in distribution tanks.

1.3 Study Objectives

The present study examines the use of physical models as an effective means of examining the contact hydraulics or flow characteristics within rectangular storage basins. The hydraulic models are then applied to observe the influence of the internal basin geometry on disinfection efficiency in terms of mixing and contact time. Physical hydraulic models simulating two water treatment plants in Edmonton, Alberta, Canada were developed for this study. Both the Rossdale Water Treatment Plant (WTP) and the E.L. Smith WTP are operated by EPCOR Water Services. The reservoir systems at both plants are rectangular basins, which use internal baffle walls to direct flow and extend the contact time of the water supply with a disinfectant before it enters the distribution system.

The first objective of this study is to gain insight into forming effective physical models that can be used for the analysis of contact hydraulics within distribution storage tanks. The effectiveness of the hydraulic models in this study will be measured by comparing the results of tracer tests from both full-scale and scaled-down versions of the two reservoir systems. Once the model is deemed effective at reproducing the primary flow processes of full-scale storage basins, it can be used to study the effects of certain design modifications. Further, the experimental arrangement could be considered as a basic arrangement to study this type of flow and once the results are analysed in terms of proper scales, the results assume general validity.

The second objective of the study is to collect and evaluate experimental data to assess the dependence of hydraulic performance on various design parameters such as the baffle wall arrangement and inlet design, and operational parameters such as the water depth and discharge. Since there is no absolute measure of the

hydraulic performance of such tanks, tracer studies are used to determine the hydraulic efficiency of each tank configuration. The effective contact time, T_{10} is determined from the resulting residence time distribution of each tracer test. The T_{10} is defined as the amount of time it takes for 10 percent of a tracer fluid added at the inlet to pass through a system. The effective detention time, T_{10}, of each design is commonly used to determine disinfection credits for CT. It is an indication of the fluid's travel time and consequently, its abilities to provide adequate mixing and retention time within the storage basin. In addition to the tracer tests, visual observations were made using a coloured dye in place of the tracer chemical. The purpose of the visualisation study is to confirm the tracer data and provide a direct method to detect short-circuiting and possible stagnant areas within each basin.

The internal configuration of the basins was modified in search of the most practical and cost effective alternative, which will provide minimal short-circuiting, minimal stagnant areas within the tank, and adequate contact time with the disinfectant. A better understanding of the relationship between the internal tank design and the consequential tank performance could lead to the development of standard design principles, which would in turn, greatly simplify the design process for storage basins.

1.4 Organisation of Thesis

The format of this thesis has been organised into five chapters. The chapter succeeding this introduction to the topic is an overview of past research into the CT concept, contact tank design, and analysis techniques used for assessing hydraulic performance of the storage reservoirs. The third chapter summarises the experimental work done in this study, which includes the design and arrangement of the hydraulic models, the experimental procedures and a brief description of each test that was conducted. Chapter 4 includes the results of the experimental measurements and the analysis completed using the data that were obtained. The

experimental results were divided into two categories: model confirmation, and the impact of internal basin modifications on hydraulic performance. The conclusions from this study are reported in Chapter 5 with recommendations of areas that need further research.

2.0 Literature Review

2.1 Drinking Water Disinfection Performance Criteria

Disinfection is an extremely important component of the water treatment process. Its function is the inactivation of disease causing microorganisms such as bacteria, viruses, and protozoa found in drinking water supplies. The conventional method of assessing disinfection levels is the use of indicator organisms such as *Giardia lamblia* cysts, which act as a gauge for whether or not pathogenic organisms are present at disease-causing levels. The premise of this method is that if indicator organisms, which are chosen due to their higher resiliency to disinfectants, are reduced to low enough levels, it will in turn ensure that pathogenic organisms are not present at disease causing levels (National Health and Welfare 1993, American Water Works Association; AWWA 1999).

The regulations for all public water systems in North America are heavily influenced by the standards set by the USEPA. The SWTR, which was developed by the USEPA and introduced in 1989 as part of the amendments to the safe drinking water act (SDWA), applies to drinking water treatment facilities that use a surface water source or ground water source under the direct influence of surface water. The SWTR requires that drinking water treatment facilities provide minimum reduction levels to control *Giardia lamblia*, enteric viruses and bacteria rather than providing an absolute organism count. The SWTR specifically requires that surface water treatment plants achieve a minimum 3-log (99.9%) reduction of *Giardia lamblia* cysts and 4-log (99.99%) reduction of enteric viruses. However, it is important to note that the reduction requirement for a particular water treatment plant will be set by its regulators and will depend on the raw water entering the facility. In order to comply with the SWTR, water treatment plants apply filtration, disinfection, or both as a means of reaching or exceeding the specified inactivation levels.

The CT concept has been adopted as the standard for determining inactivation levels. In order for a treatment facility to comply with the SWTR, it must achieve minimum CT credits, which are based on treatment techniques such as filtration and disinfection. The required CT values associated with particular levels of inactivation are provided by the USEPA in the *Guidance Manual* (AWWA 1990). The SWTR assumes that for effective filtration, a conventional treatment plant achieves 2.5-log removal of *Giardia* and a 2-log removal of viruses. A table, which includes the *Giardia* and virus reduction credits for inactivation given to various filtration processes, is included as Table 2-1 at the end of this chapter. The remaining disinfection credit, beyond that provided by filtration, is consequently earned through disinfection. In most facilities disinfection is required to meet the standards (AWWA 1999).

The SWTR also requires that a minimum of 0.2 mg/L of disinfectant enters the distribution system and that a detectable residual is maintained throughout the distribution system. In 1998, the Stage 1 Disinfectant/ Disinfection By-Product Rule (Stage 1 D/DBPR) and the Interim Enhanced Surface Water Treatment Rule (IESWTR) were added to the regulations for public water systems that use surface water sources. The Stage 1 D/DBPR sets maximum concentration limits for disinfectants and disinfection by-products. The focus of the IESWTR is to improve control over microbial pathogens, such as the protozoan Cryptosporidium, and to provide adequate protection against the increased microbial risks that may develop when systems implement the Stage 1 D/DBPR.

2.2 CT Concept

The CT concept has been adopted as a means of evaluating the level of inactivation, which can be expected from a particular disinfection process. Under the SWTR, inactivation levels are quantified using CT credits. As mentioned in chapter 1, CT is the disinfectant concentration in mg/L multiplied by the amount of time in minutes that the water is in contact with the disinfectant. It is assumed

that effective disinfection is provided when an adequate concentration of disinfectant is exposed to the water being treated, for a sufficient amount of time (Watson 1908, Hart and Vogiatzis 1982). The CT concept provides a common set of criteria for comparing the performance of a variety of processes with different disinfectants, water conditions, and flow characteristics. Determining CT credits is a simplified procedure, which takes into account the disinfection kinetics and flow hydraulics of a particular treatment chamber. Overall, CT is considered to be a relatively accurate method of evaluation for disinfection efficiency (Regli 1989).

2.2.1 Disinfection Kinetics

To understand the disinfection process, knowledge of the rate of inactivation of the indicator organism(s) by the disinfectant is essential. The Chick-Watson rate law forms the basis of the CT concept. Chick (1908) recognised the similarity between microorganism inactivation kinetics and a first-order chemical reaction, as shown in the following equation for rate inactivation:

$$\frac{dN}{dt} = -kN \qquad (2\text{-}1)$$

where k = rate constant of inactivation
N = concentration of viable microorganisms

This relationship dictates that viable microorganisms react with a chemical disinfectant to produce inactive microorganisms. Watson (1908) further developed the relationship to include the effects of changes in the disinfectant concentration. This produced the following equation for the Chick-Watson rate law:

$$\frac{dN}{dt} = k' C^n N \qquad (2\text{-}2)$$

which when integrated is:

$$\log \frac{N_t}{N_0} = k' C_t^n t \qquad (2\text{-}3)$$

where N_t = number of viable microorganisms at time t
N_0 = number of viable microorganisms at time 0
k' = rate constant of lethality
C_t = disinfectant concentration (mg/L)
n = coefficient of dilution
t = time (minutes)

The above relationship shows that for a given level of inactivation, N/No the relationship becomes:

$$C^n t = \text{Constant} \qquad (2\text{-}4)$$

In addition to being a function of the inactivation level, the constant in equation 2-4 is dependent on the target pathogen, water temperature, pH, and type of disinfectant (Clark and Regli 1990, AWWA 1999). Essentially, for a particular value of CT (disinfectant concentration multiplied by effective contact time), there is a fixed degree of inactivation at a given set of parameters such as water temperature and pH (AWWA 1999). The CT tables generated by the USEPA for the *Guidance Manual* (1990) allocate CT credit to various disinfectant, pH, and water temperature combinations. The disinfectants noted are chlorine, chlorine dioxide, chloramines, and ozone. Chlorine is the most widely used disinfectant in North America (National Health and Welfare 1993). For most disinfectants, it is assumed that the disinfectant concentration and the contact period have equal effect on the degree of inactivation, so the coefficient of dilution, n in the Chick-Watson rate law is assumed to equal unity.

The CT tables provided in the *Guidance Manual* (AWWA 1990), as part of the SWTR have been established by applying a number of simplifying assumptions (Regli 1989). For example, Chick's theory relies on the assumption that the

disinfectant concentration remains constant and in surplus for the duration of the contact time. In actuality, this is not always the case for many disinfectants. For example, chlorine is consumed during the disinfection process (Johnson et al 1998); ozone is highly reactive and non-uniform, and chlorine dioxide has a short-lived residual (AWWA 1990). As a result, the disinfectant concentration is generally lower at the end of the process than at its onset (Regli 1989). In other words, it is not uncommon for disinfectants to diverge from the first-order relationship expressed by the Chick-Watson rate law (Haas et al 1995). This may introduce error when applying this theory to extrapolate the values, which are beyond the range of experimental observations (Liem 1994). A detailed discussion on a variety of alternative kinetic models, which account for divergence from the Chick-Watson behaviour, is provided in chapter fourteen of the *Water Quality and Treatment* handbook compiled by the American Water Works Association (AWWA 1999). Another assumption pertaining to the published CT values is that for most disinfectants, it is assumed that the disinfectant concentration and the contact period have equal effect on the degree of inactivation, so the coefficient of dilution, n in the Chick-Watson rate law is assumed to equal unity. A paper by Hoff (1986) describes an extensive study supporting the validity of this assumption.

There are also inherent weaknesses in the estimation of the inactivation levels. CT inactivation is usually determined experimentally using in vitro excytation or animal infectivity (Haas et al 1994). Unique kinetics for each organism are determined experimentally in small batch or semi-batch reactors under controlled lab conditions. Regli (1989) stated that laboratory conditions do not represent actual water conditions because the test water is free of other chemicals and organic matter. Haas et al (1995) concluded that CT tables might underestimate the level of disinfection that is likely to be experienced in actual systems. A good example of the process for determining CT values is given in a paper by Robert

Clarke and Stig Regli (1990), which describes the basis for the CT values for Giardia inactivation by chlorine. This paper is provided as Appendix F of the *Guidance Manual* (AWWA 1990).

There is a large factor of safety built into the CT values provided in the USEPA *Guidance Manual* (1990) to account for many of the inherent uncertainties. As a result, the values in the CT tables are relatively conservative (Teefy and Singer 1990). There are also conservative guidelines built into the SWTR such as the recommendations that CT be measured at the peak hourly flow rate for a system, that the concentration is measured at the endpoint of the process, and that T_{10} be used as the effective contact time (Regli 1989).

2.2.2 Contactor Hydraulics

Disinfection is also a function of hydraulic efficiency. The disinfection capabilities of a system will vary with flow characteristics within the contact chamber such as backmixing, bypassing, and short-circuiting of flow. Due to these flow characteristics, some portions of the treated water will remain in the system for a longer period of time than other portions. The contact time with the disinfectant will therefore vary between different regions within the system. The time component of the CT concept is used to account for the hydraulics of a system.

Ideal flow conditions through a contact tank would consist of a plug flow condition. Plug flow is characterised as a liquid, which passes through a system with equal velocity, and does not mix with fluid that entered the system before or after it. From the inlet to the outlet, fluid in a plug flow reactor (PFR) will travel as if through a frictionless pipe, mixing completely in the axial direction without any longitudinal dispersion. Plug flow is the ideal condition because all the contents of the reactor are exposed to disinfectant for the maximum amount of time for a particular system and flow rate. The fluid remains in an idealised plug

flow system for a time equal to the theoretical detention time. The theoretical detention time, T_d, is defined as the ratio between the volume of the system from the inlet to the outlet, divided by the flow-through rate. (AWWA 1999) as shown in the following equation:

$$T_d = \frac{V}{Q} \tag{2-5}$$

where V = volume of the tank
Q = discharge

At the other end of the spectrum, there is an ideal flow condition described as a continuously stirred tank reactor (CSTR). For CSTRs, as soon as the fluid enters the reactor, it becomes perfectly mixed with all the fluid in the system. As soon as fluid enters the flow-through system, portions of it are exiting with the completely mixed contents of the tank.

In actuality, systems tend to remain somewhere between these two idealistic flow conditions. Real fluids will exhibit non-ideal flow characteristics, because velocity distributions will arise due to molecular and turbulent diffusion, and fluid viscosity will always exist to some extent in real systems (Levenspiel and Bischoff 1963). Disinfection contact time can take place in a variety of different units within the treatment sequence such as pipelines, mixing tanks, and storage reservoirs. As mentioned above, pipe flow more closely approximates a plug flow reactor, while a rapid mix chamber may approach completely mixed flow conditions. The flow in treatment units such as tanks and reservoirs include a complex combination of the attributes of both plug flow and completed mixed reactors. Concentration and temperature density differences, turbulent regions, and flow diffusion and dispersion all contribute to non-ideal hydraulic conditions. Currents within a storage tank translate into flow short-circuiting between the

inlet and the outlet, and re-circulation and stagnation zones throughout the tank. These departures from the plug flow condition result in reduced disinfection performance (AWWA 1999).

Precise measurement of the variety of deviations from ideal flow patterns that may exist within a flow through system such as a storage reservoir would be extremely difficult. It would demand the collection of enough information to define the complete flow pattern of the system. Instead, a more practical alternative has been developed, which uses measurements of the detention time of the fluid elements entering the system. Although this method does not give complete detail of the flow in the system, it provides for relatively simple experimental measurement and data interpretation. This method involves introducing a tracer into the system, collecting data for a flow through curve and interpreting its residence time distribution.

2.2.3 Tracer Tests and Residence Time Distributions

Tracer studies are the most common method used for diagnosing disinfection efficiency, and is the method recommended in the *Guidance Manual* (AWWA 1990). A tracer study is performed by injecting a tracer chemical into the fluid entering a contact chamber. The concentration at the outlet of the system is then recorded over time. The results of a tracer test can be organised into a concentration profile or flow-through curve that shows the concentration of tracer chemical exiting the treatment unit as a function of time. These values are normalised to produce residence time distributions (RTD), which are essentially graphical representations of the age distribution of fluid elements within a system such as a reservoir or tank (Levenspiel and Bischoff 1963). An RTD can be analysed to characterise the behaviour of the flow between the inlet and the outlet where the residual is measured.

There are two types of tracer tests usually conducted: the slug input test and the step input test. In the first type, a discrete amount of the tracer is introduced into the tank at once. While in the second type, the tracer is fed to the influent uniformly and continuously. Theoretically, both types would give the same results with the same accuracy.

Slug input has two advantages: it has relatively short test duration and a smaller amount of tracer is used in the test. This can be a cost benefit and a health benefit as minimal tracer is used. On the other hand, the slug input has its disadvantages. In the case of a slug input, the tracer must be very well mixed and the tracer should be added to the system as quickly as possible. Mixing is important because it prevents the formation of temperature and density gradients between the tracer solution and the water. According to Hudson (1975), the tracer should be added in a period less than 1/50 times the theoretical residence time, T_d. Another disadvantage of the slug input is that more mathematical manipulations are required for analysing the data. First, the concentration and the volume of tracer must be carefully calculated to ensure an adequate tracer profile at the outlet of the tank. The resulting concentration profile then requires further mathematical manipulation, before it can be applied to determine the conventional performance parameters. A mass balance is also necessary to determine whether tracer was completely recovered (AWWA 1990).

The step input method is often preferred by drinking water utilities, because of its simplicity (AWWA 1990). For the step input case, no mathematical manipulation is needed. The T_{10} value can be read directly from the normalised flow-through curve. The main disadvantage of the step input method is that the tracer should be added for an extended time period. Hudson (1975) recommends that at least two theoretical detention time periods be used to monitor the tracer test. The step input method requires a system, which supplies a continuous and constant flow for a

long period of time. Fortunately, these systems are typically applied in disinfection processes. For the step input method, the step RTD function is given by the F-curve as follows (Levenspiel and Bischoff 1963):

$$F(t) = C / C_0 \qquad (2\text{-}6)$$

where C = tracer concentartion at time t
C_0 = initial tracer concentration

The F-curve represents the fraction of total tracer that has passed through the system. A non-dimensional curve can be generated from the F-curve, which is already dimensionless in the vertical axis. The non-dimensional F-curve can be expressed as:

$$F(\theta) = F(T) \qquad (2\text{-}7)$$

where $\theta = t/T_d$

The shape of the F-curve for a realistic flow normally follows a pattern similar to the curve shown in Figure 2-1. The plot also illustrates a graphical representation of the F-curves for both boundary conditions, which are the ideal plug flow condition and the completed mixed flow condition.

2.2.4 Interpretation of the Residence Time Distribution

The purpose of analysing a RTD is to determine parameters, which can be related to physical properties of the flow. Interpretation of the RTD is the most common method for estimating the behaviour of the flow between the inlet and the outlet where the tracer residual is measured (Bishop et al 1993). The F-curve is essentially the age distribution of fluid elements exiting the system, and the shape of the curve gives insight into the hydraulic efficiency of a treatment unit and in turn, an approximation of its inactivation capabilities.

The conventional method for interpreting the RTD is to determine time events like T_{10} (Johnson et al 1998). These time events can be read directly from the F-curve that results from a tracer study and these parameters can then be manipulated to represent physical attributes of the flow. The performance indices commonly used in analysis are shown along with a description in Table 2-2. These time parameters are used to represent the hydraulic properties of flow such as the degree of mixing, short-circuiting, and stagnant flow.

The Guidance manual favours the use of T_{10} and T_{10}/T_d as performance indices. In order to comply with the SWTR (AWWA 1990), the T_{10} time parameter from a tracer study is used as the effective contact time in the CT value. The T_{10} is defined as the time it takes for 10% of the tracer to reach the outlet of the unit under examination. It therefore marks the moment when 90% of the fluid is retained within the basin. This means that 90% of the water has been exposed to the disinfectant for the appropriate contact time and 10% of it has had a shorter retention time (Regli 1989).

The T_{10} from a step input test is determined using numerical, and/or graphical methods (AWWA 1990). The numerical method consists of performing linear regression analysis on a semi-logarithmic plot of the dimensionless data and then calculating T_{10} using the resulting slope and intercept. However, the T_{10} is more often determined graphically, because of its simplicity. The T_{10} can be read directly from the F-curve at the point where C/C_0 equals 0.1. The results from both methods are considered to be comparable (AWWA 1990).

The ratio of T_{10} divided by T_d is called the baffle parameter. The baffle parameter is a dimensionless parameter considered as a convenient indicator of the degree of mixing (Teefy and Singer 1990). The baffle parameter normally falls within the range of 0.1 to 0.8. For ideal plug flow the T_{10}/T_d ratio is equal to unity, and

completely mixed flow is indicated by a baffle parameter of 0.1. Many studies by a list of researchers such as Teefy and Singer (1990), Bishop et al (1990, 1993), Yu et al (1991), Liem (1994), and Liem et al (1997) have incorporated the T_{10}/T_d ratio as a measure of the hydraulic performance of contact basins.

The conventional method of RTD analysis offers an estimate of tank performance based on a discrete value of the F-curve. If a small error occurs in a critical area of the flow-through curve, it can potentially give erroneous results for the conventional time parameters. It can be argued that the use of a sole data point, such as the T_{10} on the F-curve may be less accurate than alternative methods, which analyse the entire curve. However, this time parameter has the advantage of having a direct correlation to the CT value required for compliance with the SWTR (AWWA 1990).

The RTD from a tracer study may also be applied in the development and calibration of flow models that closely approximate the flow conditions in actual treatment units (Teefy and Singer 1990). Flow models offer a means of predicting the behaviour of flow without additional experimentation. The models vary in complexity and have been based on statistical and mathematical methods. Popular models for describing F-curves are statistical models such as Wolf-Resnick (1963) and Rebhun-Argaman (1965), CSTR-in series models, and dispersion models.

The Wolf-Resnick model and the Rebhun-Argaman model are statistical models that assume that flow is a composition of various flow types such as plug flow, completely mixed flow, stagnant or dead flow, and short-circuiting. Wolf and Resnick (1963) developed a theoretical relationship for defining F-curves by applying coefficients for the efficiency of mixing and phase shift to describe flow in a system. Rebhun and Argaman (1965) conducted a study comparing the Wolf-Resnick model to the conventional method. Rebhun and Argaman (1965)

modified the Wolf-Resnick model by assigning it a set of parameters with more quantitative physical meaning and re-arranging it into a linear form, as shown in the following equation (Rebhun and Argaman 1965):

$$\log[F(t)] = \frac{-\log e}{(1-m)(1-p)}[\frac{t}{T_D} - p(1-m)] \qquad (2\text{-}8)$$

where m = dead space fraction of tank volume
$1\text{-}m$ = effective fraction of tank volume
p = plug flow fraction of the effective part
$1\text{-}p$ = perfect mixing fraction of the effective part
e = fundamental mathematical constant forming the base for natural logarithms = 2.71828

This model offers insight into the degree of mixing and extent of dead space within a tank volume. These can be viewed as having more physical meaning than the time parameters of the conventional method. These models are also considered more accurate because they evaluate the entire shape of the F-curve, rather than discrete points on the curve. However, Wolf and Resnick (1963) warned that different combinations of model parameters may fit the experimental concentration curve quite accurately, but in some cases will misrepresent the actual flow characteristics. Nevertheless, with sufficient information about a particular system, a model with true physical significance could be derived. When compared to the conventional method using central tendency values, the Wolf–Resnick model showed comparable results (Rebhun and Argaman 1965). Experimental studies have suggested that the Rebhun-Argaman model may not correlate well with the initial segments of the F-curve and therefore the T_{10} parameter (Liem 1994, Bishop et al 1990). However, in general the Rebhun-Argaman model is considered to offer a more quantitative indication of the flow behaviour than conventional methods (AWWA 1999).

Continuously stirred tank reactors (CSTR) are mathematical models that apply formulation for the ideal completely mixed flow condition to estimate actual flow conditions (Chapra 1997). Real flow-through systems can be modelled by a number, N of CSTRs in series. A mass balance equation is used to evaluate the performance of a number of units of equal volume that exhibit perfectly mixed conditions. As the number of CSTRs in series increases, the performance of the system approaches that of a plug flow system. Actual systems are represented by a performance level that lies between an ideal completely mixed reactor and an ideal plug flow reactor. The number of CSTRs in series becomes a rough estimate of the real system's performance. The application of N-CSTR's in series to model flow conditions within a treatment unit provides only a simple assessment of the flow. These models are not suitable to describe the details of the complex flow patterns often produced in treatment units.

Many models employ the dispersion index, which is most commonly applied in chemical engineering studies to describe the diffusional process. It was first introduced as it applies to tracer studies by Levenspiel and Bischoff (1963) and Thirumurthi (1969) and is used as an index to the degree of deviation from ideal flow conditions. The dispersion index is calculated from the variance of the concentration curve of a slug input tracer test or an E-curve. Under plug flow conditions, it is assumed that no dispersion of the tracer chemical exists, so the dispersion index is equal to zero. Thirumurthi (1969) considers the dispersion index to be a better indicator of the flow characteristics in a system, because it takes the whole concentration curve into consideration rather than just a distinct point on the curve, as is the case for the conventional method. However, Marske and Boyle (1973) found that the Morril index, T_{90}/T_{10} is a good approximation of the dispersion index and is in fact, an easier parameter to obtain. Trussel et al (1977) discussed the use of semi-empirical formula for predicting the dispersion number in real systems.

Flow models apply a chosen set of parameters to manipulate the curve generated by the model, until it fits the tracer data. There are a wide range of design and environmental conditions that can affect tank performance, so the chosen parameters should be site specific. In many cases, it is possible for flow models to fit the experimental data more accurately when additional parameters are included, yet without physical significance it can lead to an unrealistic representation of the actual flow (Haas et al 1995). For that reason, the model limitations must be considered when applying a flow model for predictive purposes. Many of the flow models, developed to date, offer adequate insight into the general flow pattern of a system, but do not offer a detailed quantitative description of the complex flow patterns involved. Levenspiel and Bischoff (1963) proclaimed that although the RTD for a system may not provide a detailed account of the flow patterns, it does provide an adequate description of the flow conditions within a system, with or without the use of flow models.

2.3 Disinfectant Residual in the Water Distribution System

As mentioned earlier, the SWTR performance criteria include requirements that a minimum disinfectant concentration enters the distribution system and that a detectable residual is maintained throughout the distribution system. The purpose of a persistent disinfectant residual in the distribution system is to provide post-treatment protection to the consumer. The distribution system includes a complicated network of piping that is designed to supply the public with a continuous source of safe drinking water. It is unwise to presume that the distribution system is biologically sterile, or that it is completely exempt from the risk of contamination (AWWA 1999). A disinfectant residual can reduce or prevent the re-activation of pathogens and colonization by surviving organisms in the distribution system's pipe network (AWWA 1999). It also provides protection against bacteria that may enter the distribution system (AWWA 1999).

The importance of the requisite disinfectant residual in the distribution system is clear. However, the goal of providing adequate post-treatment protection of drinking water rivals the desire to minimise harmful disinfection by-products. The struggle for drinking water authorities then becomes finding the balance between reducing the amount of by-products, and maintaining distribution system integrity. Tipping the scales in the wrong direction can have grave consequences, as the concerns deal with public health. For example, in the 1980's, out of concern for the potential health risks of disinfection by-products, the authorities in Peru eliminated chlorination of many of Lima's drinking water wells. In January 1991, there was an outbreak of cholera in Peru and by November of the same year, more than 300,000 people were infected, and more than 3,500 were dead. Though there is some debate over the cause of the epidemic, it is apparent that the water supplies were compromised by the lack of chlorine. Chlorination may be the most effective method for destroying cholera bacterium, and in its absence the cholera epidemic was able to penetrate the water supply and spread through the population quickly and easily. It is believed that the cholera bacteria entered the water supply via ageing pipes and open wells, after the water was treated through the established filtration process (Anderson 1991).

Presently, chlorine is the most common disinfectant used in North America. There is debate about the use of disinfectants such as chlorine due to the potential for harmful by-products that result from its reaction with organic matter and other disinfectant by-product (DBP) precursors (National Health and Welfare 1993). All disinfectants produce by-products, but those associated with chlorine have been more actively studied. DBPs of the chlorination process that are under scrutiny include Trihalomethanes (THMs), Haloacetic acids, bromate and a number of other possible by-products. There is concern that several of the DBPs may contribute to long term adverse health effects in humans. DBPs have been

linked to colon and bladder cancer, as well as other pathological effects in laboratory animals (National Health and Welfare 1993). A useful review of disinfectant by-products is included in *Water Treatment Principles and Applications* (National Health and Welfare 1993, p132). A few techniques have been applied in order to minimise disinfectant by-products while maintaining water quality in the distribution system. The options include the removal of DBPs after formation, the removal of DBP precursors, alternative chemical disinfectants, and the later addition of disinfectant. The removal of DBPs and DBP precursors can be an expensive undertaking. The options include granular activated carbon and ozonation to remove either DBPs or their precursors, enhanced coagulation focused on the removal of precursors such as organic material, and selection of an alternative source water for minimising DBP precursors (National Health and Welfare 1993). Many European countries focus on controlling degradable organic matter in the distribution system rather than maintaining disinfectant residuals (AWWA 1999). Alternative disinfectants such as ozone, chlorine dioxide, chloramines, and ultraviolet radiation (UV) can be used in place of chlorine to reduce DBPs. However, the ability of some of these alternative disinfectants to preserve an acceptable microbial quality throughout the distribution system is questionable (AWWA 1999).

Disinfectant can be added at a number of different stages in the water treatment sequence. Contemporary methods, used in the treatment of drinking water, encourage disinfectant application in the later phases of the treatment process (National Health and Welfare 1993). A disinfectant added at the later phases of the treatment sequence, such as within the storage reservoirs at the end of the process, can provide significant benefits. If chlorine is added in the later stages of the treatment process, the amount of organic material that it will come into contact with will have been greatly reduced. This in turn decreases the amount of DBPs produced by the process. In addition, chlorine added at later stages of the

treatment process improves the probability of maintaining the required disinfectant residual in the distribution system.

Depending on their use, disinfectants can be either helpful or harmful in the treatment process. If more than the required amount of a disinfectant such as chlorine is added to the system, it could contribute to increased chemical costs, and increased consumer complaints regarding the taste and smell of the chemical in the drinking water, as well as a possible increase in DBPs (AWWA 1999). Because drinking water supplies are also used for lawn irrigation and industrial processes, a surplus of disinfectant in the drinking water could also result in an increase in chemical entering into the environment. The treatment option chosen to minimise the formation of DBPs should be practical, cost-effective and most importantly it should offer the lowest risk to the consumer. The strategies applied for the reduction of DBPs in drinking water should be based on an informed risk assessment (Sobsey et al 1993). There is a need to establish a more complete assessment of both the microbial risks and the risks regarding DBPs, in order to make a fair comparison between the risks of exposure to microbial pathogens and the risks of disinfection chemicals and their by-products (Sobsey et al 1993). More research is required to improve the risk assessment process by including societal factors such as death, quality of life, and cost (Sobsey et al 1993).

2.4 Use of Storage Tanks in the Disinfection Process

2.4.1 General

Storage basins are often the largest and most visible component of the water treatment train, and are normally positioned as the last unit before the distribution system (AWWA 1999). The primary purpose of storage basins is to store large quantities of drinking water, which is needed to supply population demands, and maintain positive pressures throughout the distribution system. If properly designed, these tanks can also contribute greatly to the disinfection process as disinfectant contact basins. Storage reservoirs are an ideal venue for disinfection,

because the immense tanks can provide for prolonged contact times, while the addition of disinfectant near the end of the treatment process may reduce DBPs and allow for sufficient disinfectant residual to enter the distribution system. However, in order for storage reservoirs to act as effective contact chambers, they need to be designed to provide adequate mixing and retention time. Since storage tanks are already an integral part of the water treatment process, designing or modifying the internal arrangement of these tanks to promote a dual function as a contact chamber, can be a relatively inexpensive method for improving the quality of the treated water.

Storage basins do not naturally exhibit the ideal hydraulic characteristics of a disinfectant contact chamber. Without proper design of the internal tank configuration, the hydraulic conditions will significantly diverge from the ideal plug flow condition, and exhibit fluid short-circuiting and pockets of stagnant water. When water takes a 'short-cut' from the inlet to the outlet, the flow is short-circuiting. If there is flow short-circuiting within the basin, then some of the flow is exposed to the disinfectant for an insufficient duration, or contact time. As a result, inadequately treated water could potentially reach a consumer's faucet. On the other end of the spectrum, if a volume of water remains within the tank for an extended time period, often far exceeding the theoretical detention time, it is dubbed as dead flow or stagnant flow. The implications of dead flow zones or stagnant flow areas include the potential for water quality to degrade after prolonged storage times, which could result in taste and odour problems, bacterial colonisation or the re-activation of microbial pathogens (AWWA 1999, Rossman and Vidal 1997).

It should be noted that there are limited operational controls available to correct inherent design errors in storage reservoirs (Hart and Gupta 1978). When the internal basin design results in inadequate mixing and contact time, the chlorine dosage offers one of the only operational controls (Falconer and Tebutt 1986).

However, if the chlorine concentration is increased to reach the required level of inactivation it could potentially increase both the operational costs and the environmental and health impacts related to higher chemical concentrations in drinking water.

2.4.2 Current Design Practices for Rectangular Contact Basins

The internal geometry of a contact basin has a significant impact on the hydraulics of the flow-through system. Popular installations used for improving the hydraulic efficiency of storage basins are baffle walls, and inlet or outlet modifications such as weirs, baffles and diffusers. These additions are relatively inexpensive alternatives and normally quite simple to install. Operational variables such as water depth and flow rate have also been shown to effect the hydraulic performance of the reservoirs and should be considered during the design process.

The internal baffle configuration within contact basins is normally positioned in a manner that will guide the flow in a serpentine motion through the tank, thereby extending the travel distance of the fluid. The addition of baffle walls has been shown to increase the fluid retention time and decrease flow short-circuiting in reservoirs. This general trend has been explored by a number of researchers such as Falconer and Tebutt (1986), Regli (1989), Bishop et al (1990,1993), and Liem et al (1997).

The ratio of the length of travel to the channel width (L:W) created by the baffle conditions has been the focus of many studies aimed at deriving a relationship between the geometry and the hydraulic performance of contact basins. The L:W ratio increases as the number of channels within the confines of the tank increase. The channels provide a longer travel distance, but as a consequence a narrower width of channel for the flow to travel. Marske and Boyle (1973) studied the dependence of the dispersion number on the L:W ratio and demonstrated that there is a significant decrease in the dispersion number as the L:W ratio increases.

The results of a study conducted by Mitha and Mohsen (1990) compared well with findings of Marske and Boyle (1973). Bishop et al (1990, 1993) agree that an improvement in the hydraulic efficiency occurs as the L:W ratio increases, but that improvements from baffle installations are limited and that an optimal value for the L:W ratio exists. They observed that the values for T_{10}, the Morril index, and the dispersion index did not significantly improve beyond a L:W ratio of 20:1 for a square basin tested in the study. In the *Standards and Guidelines for Municipal Waterworks, Wastewater and Storm Drainage Systems* by Alberta Environmental Protection (AEP 1997), it is recommended that contact chambers be built with baffle walls parallel to the longitudinal axis of the tank and have a length-to-width ratio of no less than 40:1.

The *Guidance Manual* (AWWA 1990) includes a baffling classification system developed from tracer studies conducted by Marske and Boyle (1973) and Hudson (1975). The baffle parameter, T_{10}/T_d was determined for a number of different internal tank designs, which are summarised in Table 2-3. The table includes a description of the design characteristics and a qualitative rating scale from poor to superior baffling conditions that are assumed to be associated with each baffle parameter. The values were determined empirically with a particular focus on design characteristics such as the degree of baffling, inlet baffling and outlet weir configuration. The baffle parameter increases as the baffle conditions and basin design improves. A collection of illustrated examples of each level of baffling conditions for both rectangular and circular contact tanks are provided in Appendix C of the *Guidance Manual* (AWWA 1990). When conducting tracer studies is not a practical alternative, it is recommended that the T_{10} of a contact basin be estimated by referencing these typical baffling designs (AWWA 1990). Bishop et al (1993) and Teefy and Singer (1990) show that the T_{10} values may be overestimated by this method, and that the actual conditions tend to be worse for the unbaffled conditions. However, rectangular basins compared fairly well for

average to superior baffling conditions despite the fact that the tanks that were tested had no inlet or outlet baffles.

Baffling in the vicinity of the inlet and the outlet is a prevalent component of the baffling description in the previously mentioned classification levels. A number of studies have investigated the affect of inlet and outlet conditions. Rebhun and Argaman (1965) tested a sedimentation basin with an inlet baffle and found that when the baffle was removed, a decrease in the hydraulic performance was indicated by a number of the conventional parameters. In a study by Mitha and Mohsen (1990), perforated baffles were installed at the inlet and outlet to achieve uniform flow. The inlet diameter is a topic of discussion in Rossman and Vidal (1997). Falconer and Tebutt (1986) conducted model and field measurements and found that a significant improvement to tank performance can be attained by modifying the height and width of a submerged inlet weir. The *Guidance Manual* (AWWA 1990) indicates that the outlet conditions tend to have a stronger impact on the T_{10}/T_d than the inlet conditions.

The effects of operational conditions such as water depth, discharge and temperature should also be addressed when considering the hydraulic performance of storage basins and contact chambers. These operational conditions are known to fluctuate in storage tanks in order to meet system demands. The *Guidance Manual* (AWWA 1990) states that a falling water depth in a storage basin is likely to lower the value of T_{10}. As a result, it is recommended that the effective detention time only be used for calculating CT, when the basin is operating at a water depth at or above the depth used in the tracer test.

In general, as the discharge increases the T_{10} decreases. The *Guidance Manual* (AWWA 1990) suggests that to determine the dependency of T_{10} on discharge for a treatment unit a minimum of four tracer tests should be conducted at a range of

flow rates. A curve can be fit to the data and T_{10} values for other discharges can be interpolated from the curve. Yu et al (1991) found that the data fit a curve of the form:

$$T_{10} = aQ^b \qquad (2\text{-}9)$$

where a, b = regression coefficients
Q = discharge

If it is impractical to perform a range of tracer tests, then the data from one test that is conducted at a minimum of 91% of the maximum operational discharge should be used to estimate values of T_{10} at equal or lower flow rates (AWWA 1990). In that case, a simple linear correlation is used, which is provided in the *Guidance Manual* (AWWA 1990) and takes the form:

$$T_{10S} = T_{10T}[\frac{Q_T}{Q_S}] \qquad (2\text{-}10)$$

where T_{10S} = T10 at system discharge
T_{10T} = T10 at tracer discharge
Q_T = tracer study discharge
Q_S = system discharge

Liem (1994) states that estimations of T_{10} made only from known T_{10} and discharge values may not be correct since depth, volume and other factors are excluded.

Water temperature is an operational condition, which can impact both the disinfection kinetics and the hydraulic performance of a contact basin. Changing seasonal conditions may induce temperature variations at water treatment facilities. These temperature variations may heighten the potential for thermal

stratification, which may in turn influence the detention time of the reservoirs (AWWA 1990).

Researchers have not yet standardised a consistently reliable and cost-effective method for designing and testing contact reservoirs. More data collected through tracer studies is required to help refine and solidify general trends developed by research to this point. Bishop et al (1990) suggest that further research concentrate on gathering information on the effects of inlet and outlet design, depth fluctuations, flow condition, and L:W ratio optimisation. Clark et al (1996) recommend that future research be focused on learning more about the affects of operating conditions, geometric configuration, and inlet/outlet positions on the mixing conditions. Future research will enhance the design process by leading to more accurate associations between physical design characteristics and efficiency parameters.

2.4.3 Hydraulic Modelling to Assess Contact Tank Performance

The purpose of hydraulic models is to replicate the full-scale conditions of hydraulic structures. It is important that the principal flow processes in a system are effectively reproduced in the model, so that the results of a model study are meaningful and can be related to the full-scale system. This is achieved by employing the principles of similitude and dimensional analysis in the design of the hydraulic models. It is very difficult and impractical to attain the full scope of similitude criteria associated with a hydraulic system, as no more than one requirement for dynamic similitude of flow can be reached at one time. For that reason, a competent knowledge of the dominant physical processes within a system as well as an awareness of a model's shortcomings or scale effects is fundamental in developing a successful model (ASCE 2000). Good judgement is important for identifying which processes are dominant in a particular situation and to make design decisions that minimise scale effects. Judgement is however, a

variable dependent on the skills and experience of the modeller and can therefore be inconsistent. For this reason, guidelines need to be developed which specify the criteria required to conduct a successful model study of contact basins.

For free-surface flow conditions, the inertial and gravitational forces are the dominant forces that define the hydrodynamic flow conditions. As a result, adherence to the Froude criterion for dynamic similarity is normally applied in the development of scale models of storage basins. Many researchers such as Hart et al (1975), Falconer and Tebutt (1986) and Bishop et al (1990, 1993) have found that using the Froude number as the key force ratio, which must be equal in the model and in the prototype, will result in similar tracer response curves for both. Hart and Gupta (1978) do not strictly adhere to the Froude criterion. They argue that because complete dynamic similarity is not possible, models should be designed according to the response curve similitude. They suggest that a smaller discharge than implied by the Froude criteria may be a better representation of the hydraulic attributes of this type of system. Hart (1979) and Hart and Vogiatzis (1982) performed further studies using this method and found similar results.

The ability of a physical model to predict the actual situation also depends on the size of the model. It is advisable to construct the largest model possible to ensure reasonably sized model depth and model flow rates (Bishop et al 1993). This helps to minimise the scale effects or deficiencies that occur when scaling down a hydraulic system (ASCE 2000). For example, Mitha and Mohsen (1990) found that the normal variance and the dispersion number exhibit scale effects in smaller models, but if models are large enough they become scale independent. As a result, they concluded that if the model is large enough, the dispersion number can be assumed to be the same in the prototype, and that the concentration curve can be predicted from the model.

As in the case of the dispersion number, scale can affect many of the efficiency parameters that are commonly associated with tracer analysis. Many studies such as those conducted by Hart et al (1975), Falconer and Tebutt (1986), and Bishop et al (1990, 1993) found fairly good correlation between the model and prototype values for certain efficiency parameters. However, according to Hart and Gupta (1978), these performance indices can vary in their ability to simulate the full-scale performance. By examining the affects of model discharge on a number of different flow distribution parameters, they found that some were more reliable than others at simulating the actual prototype responses. It is advisable to examine the ability of the applied performance indices to mimic prototype flow characteristics in the first phase of a hydraulic model study (Hart and Gupta 1978).

Another topic to note, when discussing hydraulic models, is whether distorted models can adequately simulate the full-scale situation. Falconer and Tebutt (1986) examined the use of both distorted and undistorted models of contact tanks and concluded that the results of both were comparable with full-scale field measurements. Most of their tests applied an undistorted model with a Reynolds number at the lower end of turbulence. The distorted models included vertical distortion of two and three times the horizontal scale, which translates to a water depth of two to three times those of the undistorted models. The advantages of vertically distorted models include increased Reynolds number in terms of flow depth, and increased accuracy of flow-velocity and depth measurements (ASCE 2000). However, this improvement with respect to kinetic similitude, is often at the cost of geometric and dynamic similitude. More information on vertical distortion of free surface flows can be found in *Hydraulic Modeling Concepts and Practice* (ASCE 2000 p69-73).

Scale models provide a convenient site for visual observation of the flow characteristics within contact basins. A visual examination can be done relatively easily and inexpensively in physical models using a coloured dye. Hart et al (1975) used black ink placed in point locations at three separate depth elevations to observe the current patterns through a contact chamber. Falconer and Tebutt (1986) used both floats and dye to observe the velocity field and re-circulation zones in chlorine contact tanks. Observation of a dye cloud travelling through a basin offers insight into the location of dead flow zones and short-circuiting. Although qualitative in nature, this knowledge is a great advantage when assessing flow characteristics, because it provides the investigator with confirmation of the trends determined from the tracer response curve, and a broader perspective of the hydraulic activity within the tank. In both the aforementioned studies, the visual observations agreed with the time ratios observed from tracer analysis.

Table 2-1. Giardia and Virus Reduction Credit for Filtrati
(adapted from AEP 1997)

Treatment	*Giardia* Credit	Virus Credit
Conventional Filtration	2.5 log	2.0 log
Direct or In-line Filtration	2.0 log	1.0 log
Slow Sand Filtration	2.0 log	2.0 log

Table 2-2. Performance Parameters Commonly Used in Conventional Analysis of Contact Basins (adapted from Marske & Boyle 1973)

Parameter	Definition
T_D	Theoretical detention time
t_i	Time interval for initial indication of the tracer in the effluent
t_p	Time to reach peak concentration
t_g	Time to reach the centroid of the affluent curve
T_{10}, T_{50}, T_{90}	Time for 10, 50, and 90% of the tracer to pass at the effluent end
t_i/t_R	Index of short-circuiting (approaches to a value of 1.0 for PFR)
t_p/t_R	Index of modal detention time (approaches to a value of 1.0 for PFR)
t_g/t_R	Index of average detention time (approaches to a value of 1.0 for PFR)
T_{50}/t_R	Index of mean detention time (approaches to a value of 1.0 for PFR)
T_{90}/T_{10}	Morril dispersion index, indicates degree of mixing

Table 2-3. Typical Baffling Conditions
(adapted from the USEPA *Guidance Manual* 1989)

Baffling Condition	T_{10}/T_D	Description
Unbaffled (mixed flow)	< 0.1	None, agitated basin, very low length to width ratio, high inlet and outlet flow velocities
Poor	0.3	Single or multiple unbaffled inlets and outlets, no intra-basin baffling
Average	0.5	Baffled inlet or outlet with some intra-basin baffles
Superior	0.7	Perforated inlet baffle, serpentine or perforated intra-basin baffles, outlet weir or perforated launders
Perfect (plug flow)	1.0	Very high length to width ratio (pipeline flow), perforated inlet, outlet, and intrabasin baffles

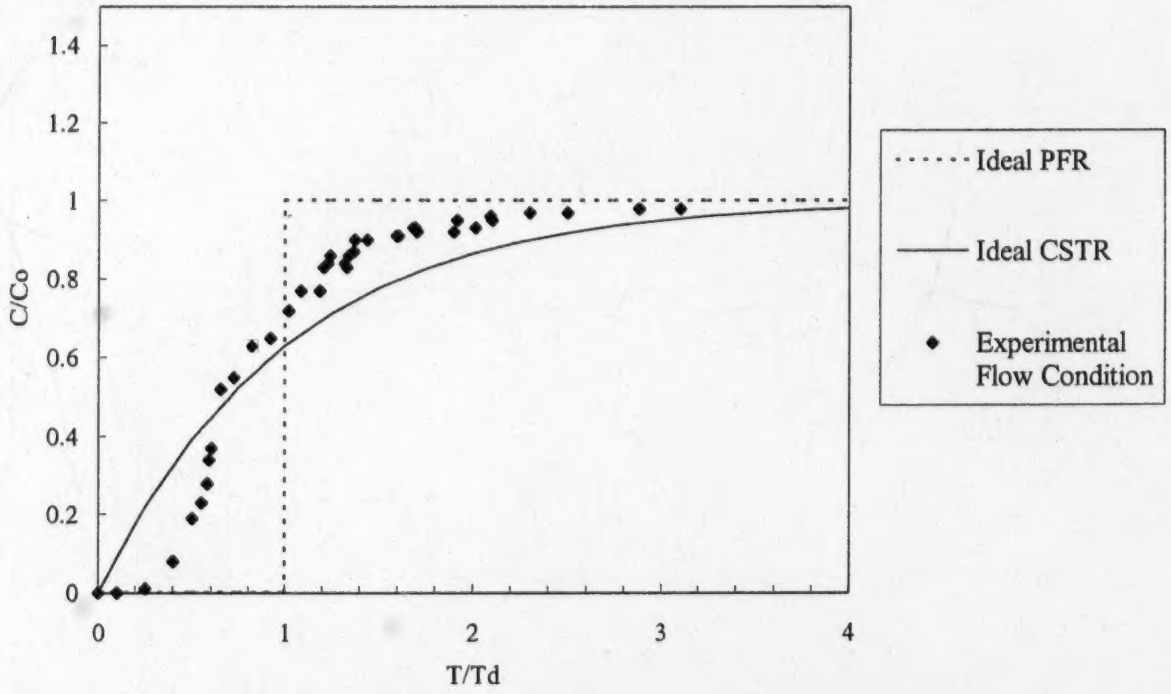


Figure 2-1. Residence Time Distribution for a Step Input Tracer Study (F-curve)

3.0 Experimental Arrangement, Procedures and Experiments

3.1 Model Description

3.1.1 Similitude

Before a hydraulic model can be built, it is important to determine the most appropriate model to prototype scale ratios so that values measured in the model may be scaled up to reflect values found in the prototype. These scales are calculated with consideration for the principles of similitude and dimensional analysis. Similitude is a method, which uses dimensionless parameters to relate elements of a process occurring in a model to the same elements occurring in a prototype. Dimensional analysis is a means of distinguishing the most important dimensionless parameters associated with a particular hydraulic process. It is primarily influenced by the principle of dimensional homogeneity, which requires that all terms of a correct equation have the same dimensions. Combined with a good understanding of the physical processes in a hydraulic system, the principles of similitude and dimensional analysis can be used to provide the appropriate scale factors for a model study. By identifying the important parameters in a system, these methods not only yield the laws necessary to successfully scale-down the system, but also offer a simplification of the problem, and guidance for experimental examination of the problem (Sharp 1981).

Hydraulic models are usually designed as smaller geometrically similar versions of the prototype. The length scale is the primary scale for any hydraulic model and its value relies on both the type of system to be modelled and on the space available for model construction (Sharp 1981). Geometric similarity is not enough to produce similar flow patterns at different scales. The successful design of a hydraulic model also depends on kinematic similarity and dynamic similarity. Kinematic similarity exists when there is a constant ratio between corresponding velocities and between corresponding accelerations at geometrically equivalent positions in the model and prototype. Dynamic similarity exists when the forces at

a position in the model are in a constant ratio with the forces in the prototype at an equivalent position. For a model and prototype to be dynamically similar, they must also already possess both geometric and kinematic similarity.

Many forces can affect a particular fluid system, examples include the force of gravity, viscous forces, surface tension forces, and the forces due to pressure differences. Most fluid systems also include the hypothetical force of inertia, which is related to the acceleration or deceleration of flow. It is common practice to identify the most important dimensionless parameters used for dynamic similarity by taking the ratio of the dominant force of the system and the inertial force (ASCE 2000). The inertial force is related to mass and acceleration using Newton's second law:

$$F_i = Ma \tag{3-1}$$

where F_i = force of inertia
M = mass
a = acceleration

This can be expressed with the following equation by applying the dimensional analysis of acceleration and knowing that mass is proportional to ρL^3.

$$F_i = \rho L^2 U^2 \tag{3-2}$$

where ρ =density
L = a characteristic length
U =velocity of flow

If even feasible, it is extremely difficult and impractical that more than one requirement for dynamic similitude of flow is reached at one time. For that reason, it is important to identify the forces that predominantly affect the system under analysis. In the case of water distribution tanks, the flow enters the system as a turbulent jet, circulates around the baffle walls and towards an outlet point where it is withdrawn. The water circulating in the basin is a free surface flow. In

most cases, a free surface flow is regarded as a gravity-dominated phenomenon; therefore the acceleration of gravity is likely to be an important parameter in this system. Water is the most practical, accessible and economical fluid for operating the storage tank model. Unfortunately, if the same fluid (water) is used in the scale model as in the prototype and the systems are affected by gravity, as is the case for most hydraulic systems, then either gravity or fluid viscosity must be assumed negligible. This assumption is required because neither the viscosity of water, nor the earth's gravity is scaled. The flow entering the storage tank is turbulent, which indicates that dynamic viscosity is likely to have little effect on the system in comparison with the effects of gravity. It is therefore assumed that in the case of storage basin hydraulics, gravity is more important than fluid viscosity.

When a system is dominated by gravity alone, density may be disregarded because it possesses the only mass dimension. For hydraulic systems operating with water, compressibility tends to have a negligible effect and can also be disregarded. In this study, the forces caused by surface tension can also be ignored for both the model and prototype, because both systems are large enough for these forces to have very little effect.

If viscosity is neglected and gravity is deemed the most influential force in this hydraulic system then the Froude number is used to develop model scale factors. The Froude number is the ratio of inertial force to the force of gravity:

$$F_g = \rho g L^3 \tag{3-3}$$

$$\therefore \frac{F_I}{F_g} = \frac{\rho L^2 U^2}{\rho g L^3} = \frac{U^2}{gL} \tag{3-4}$$

where F_g = force of gravity
g = acceleration of gravity

The Froude number, F_r is expressed as:

$$F_r = \sqrt{\frac{U^2}{gL}} \tag{3-5}$$

In cases where gravity forces are the most important influence on a system, the Froude number should be equivalent for the model and prototype. According to the Environmental and Water Resources Institute of the American Society of Civil Engineers (ASCE 2000), the Froude number is the most common criteria applied for similarity of hydraulic models. In the case of distribution storage tanks, it has been used as modelling criteria by researchers such as Hart and Gupta (1978), and Rossman and Vidal (1997).

By employing the Froude number criterion for similitude, the prototype to model scale factors may be developed as follows:

$$F_{rm} = F_{rp} \tag{3-6}$$

$$\sqrt{\frac{U_m^2}{g_m L_m}} = \sqrt{\frac{U_p^2}{g_p L_p}} \tag{3-7}$$

where F_{rm} = force of gravity in the model
F_{rp} = force of gravity in the prototype
U_m =velocity of flow in the model
U_p =velocity of flow in the model
g_m = acceleration of gravity in the model
g_p = acceleration of gravity in the prototype
L_m = a characteristic length in the model
L_p = a characteristic length in the prototype

Assuming that gravity is constant over the surface of the earth, the velocity scale is:

$$\frac{U_p}{U_m} = \sqrt{\frac{L_p}{L_m}} = \sqrt{\lambda} \tag{3-8}$$

where λ is the length scale, L_p/L_m

The ratio of model to prototype area is therefore:

$$\frac{A_p}{A_m} = \frac{L_p^2}{L_m^2} = \lambda^2 \qquad (3\text{-}9)$$

where A_m = area in the model
A_p = area in the prototype

The ratio of model to prototype volume is:

$$\frac{V_p}{V_m} = \frac{L_p^3}{L_m^3} = \lambda^3 \qquad (3\text{-}10)$$

where V_m = volume in the model
V_p = volume in the prototype

The scale ratio for time is:

$$\frac{T_p}{T_m} = \frac{L_p / U_p}{L_m / U_m} = \left(\frac{L_p}{L_m}\right)\left(\sqrt{\frac{L_m}{L_p}}\right) = \sqrt{\frac{L_p}{L_m}} = \sqrt{\lambda} \qquad (3\text{-}11)$$

where T_m = time in the model
T_p = time in the prototype

Finally, the scale law for discharge is:

$$\frac{Q_p}{Q_m} = \frac{L_p^3 / T_p}{L_m^3 / T_m} = \left(\frac{L_p}{L_m}\right)^3 \left(\frac{L_m}{L_p}\right)^{0.5} = \left(\frac{L_p}{L_m}\right)^{2.5} = \lambda^{2.5} \qquad (3\text{-}12)$$

where Q_m = discharge in the model
Q_p = discharge in the prototype

If the Froude number is the appropriate criterion for similarity between the prototype and model for the case of distribution storage basins, then the hydraulic

model should reproduce the physical processes, which occur in the system that it is trying to imitate.

3.1.2 Model Scale

It is advisable to construct the largest model possible to ensure reasonably sized model and model flow rates. This helps to minimise the scale effects or deficiencies that occur when scaling down a hydraulic system (ASCE 2000). Both models used in this study were built and operated in the T. Blench Hydraulics laboratory at the University of Alberta in Canada. With consideration for both scale effects and the amount of laboratory space available for construction and operation of the models, a model to prototype length scale, L_p/L_m of 26.4 was chosen for the combined reservoir system of the Rossdale WTP. The E.L. Smith model was constructed subsequently by altering the existing Rossdale model, therefore leading to a L_p/L_m of 47.46.

Application of the Froude criterion, as illustrated in the preceding section of this chapter, combined with the above length scales were used to determine the prototype to model scale factors applied in this study. The scale factors for pertinent quantities in reference to both the Rossdale and E.L. Smith storage basin models are presented in Table 3-1.

Verification that the viscosity is negligible for both the prototype and the model, thereby ensuring the appropriateness of the Froude criterion is an important step in a model study. It is a widely accepted assumption that molecular viscosity can be neglected when the Reynolds number, R_e is greater than a few thousand. For the purpose of this study, it was confirmed that all rates of inflow for both the models and the prototypes produced a sufficiently large Reynolds number to generate a fully turbulent jet at the entrance of the tank. The Reynolds number is expressed as:

$$\text{Reynolds number} = R_e = \frac{UL}{\nu} = \frac{Inertial_Force}{Viscous_Force} \qquad (3\text{-}13)$$

where ν = kinematic viscosity for water, can be approximated as 10^{-6} m^2/s.

3.1.3 Arrangement of the Rossdale Model

The first storage tank model that was built for this study was the Rossdale water treatment plant's combined reservoir system, which is illustrated in Figure 3-1. Information on the layout of the system was made available from drawings submitted by EPCOR Water Services. The dimensions provided in these drawings were appropriately scaled down using the fore mentioned scaling factors. The model was then constructed of a wooden floor with 420 mm tall side walls made from sheets of clear acrylic plastic. The reservoir system consists of two rectangular storage basins, referred to as the east cell and the west cell. A photo of the model is included as Photo Plate 3-1. The dimensions of the Rossdale model are shown as a plan view diagram in Figure 3-2.

For most of the experiments, there were two tanks supplying water to the model. One tank solely contained city water and the other held a solution of tracer chemical and city water. Fresh water was withdrawn from the first tank until the water level in the two cells of the reservoir model was stable. For the last group of experiments: R24 through to R31, the fresh water tank was replaced by a hose connected to a city water source. The water elevation inside the model was selected by adjusting a constant head tank, which was placed at the outlet. When the water level inside the model was stable, the fresh water supply was shut off and the solution containing the tracer chemical was introduced from the second supply tank at the same specified discharge. The second tank, hereby referred as the jet tank, supplied the model with a mixture of water and tracer chemical at a constant flow rate throughout each experiment. Photo Plate 3-2 is a photo of the jet tank and Figure 3-3 shows the details of the jet tank. The solution was re-

circulated to the jet tank in the form of three circular turbulent jets, each with an approximate diameter of 19 mm. The jets helped to keep the contents of the jet tank well mixed and homogeneous. A step input type of tracer test was chosen for this study, so it is important to select a mechanism such as this, which provides a continuous and constant discharge to the tank as required for the duration of each test.

A Model 1114, Brooks full-view flowmeter was placed at both of the feeding lines in the model to measure the discharge. A photo of the two flowmeters is included in Photo Plate 3-2. Flow to the model was controlled using four valves, two on each feeding line. The two feeding lines are referred to as Line #1 and Line #2, as shown in Figure 3-2. Water was generally supplied to the system through Line #1, which was located in the east cell. Line #1 is a pipe with an inside diameter of 1350 mm in the prototype and a 51mm diameter in the model. The pipe was connected to the basin as a submerged inlet of equal diameter. Due to piping limitations at the water treatment plant, at flows greater than 150 ML/d, a portion of the water entered through the west cell directly, totally bypassing the east cell. When this occurred the portion of flow exceeding 150 ML/d was directed to Line #2, which was also a 1350 mm diameter pipe. The overflow entered the west cell through another submerged entrance, which will be called the overflow inlet. Each pipe allowed for a maximum discharge of 150 ML/d, so the largest prototype discharge capable of coming into the two cells is 300 ML/d, which translates to a value of 58.2 L/min for the model.

The flow in the model travels from the east cell into the west cell through a fully submerged circular entrance called the intercell outlet. This entrance had a diameter of 57 mm and was cut through the 10 mm thick, clear acrylic plastic, which separates the two model reservoirs. The centre of the intercell outlet was located 330 mm from the side of the model and 70 mm above the wooden floor.

The flow exits the system through a pipe in the floor of the west cell. It has an inside diameter of 57 mm and is referred to as the outlet. The location of the inlet, the overflow inlet, the intercell outlet, and the outlet in the Rossdale model have been labelled in Figure 3-2.

3.1.4 Arrangement of the E.L. Smith Model

The E.L. Smith model was constructed by altering the existing Rossdale model. The reservoir at the E.L. Smith WTP is a square basin consisting of only one cell as shown in Figure 3-4. There is one inlet, one outlet and a 75 000 mm baffle wall located down the centre of the basin. A plan view diagram of the basin with model dimensions is provided as Figure 3-5 and a photo of the model is presented in Photo Plate 3-1.

Much like the Rossdale model, the reservoir was supplied by both a fresh water source and by the previously mentioned jet tank. The fresh water was provided through a hose that was connected to a city water supply. As before, when the water level inside the reservoir was stable, the fresh water was shut off, and the tracer solution was introduced from the jet tank. Water was pumped to the tank through a 40 mm diameter hose connected to the inlet pipe. The flow was measured using a Brooks full-view flowmeter placed at the feeding line. The flow to the tank was controlled using two valves.

The inlet to the storage basin is a submerged circular pipe with a 1500 mm diameter. The inlet pipe is located 9950 mm from the west corner of the cell and positioned perpendicular and flush with the southwest wall of the basin. The model inlet has a 32 mm diameter and its centre is positioned 210 mm from the corner of the basin. The outlet for the E.L. Smith model also has a 1500 mm diameter (32 mm model). The outlet is positioned along the northeast wall of the

reservoir with its centre set at 13420 mm (280 mm model) from the north corner. The E.L. Smith model used a constant head tank installed at the outlet of the cell for the purpose of adjusting the water elevation.

3.2 Application of Rhodamine WT as a Dye Tracer

A tracer for water systems is most effective if it is a stable, non-toxic, economical and a highly detectable compound. Additionally, it should be easily measurable in low concentrations (Wilson et al 1986). The chemical chosen for this study was Rhodamine WT because it is a commonly used chemical, which meets the preceding requirements and is considered easy to use (Wilson et al 1986). In a 1977 study that evaluated a number of fluorescent dyes, Smart and Laidlaw recommended its use as a dye tracer. Rhodamine WT is a highly fluorescent substance, which is also known as Intracid, and it is available commercially at a concentration of 20 percent by weight with a specific gravity of 1.19. Rhodamine WT is measured using fluorometry, which assesses levels and types of fluorescence.

Fluorescent dyes have been widely accepted as water tracers since the 1960's (Wilson et al 1986). Applications for the use of fluorescent tracers include discharge measurements, time of travel measurements, the identification of dispersion patterns, and as in this case, for determining contact chamber efficiency. Fluorescent materials absorb light of a certain wavelength from an external source and almost immediately emit a light of a different wavelength. When the external light source is removed, the chemical stops irradiating light. The theory of florescence explains that energy from the external light source is absorbed, which causes electrons from within the molecules to elevate to a higher energy level and larger orbit, this is referred to as excitation. Then as the excited electrons return to ground state, energy is emitted. According to Stoke's law, energy is almost always emitted at a lower energy, and therefore longer

wavelength than the absorbed energy. A fluorescent substance can be identified by the combination of excitation and emission spectra, which is specific to that material. Each fluorescent chemical is described using the maximum levels for excitation and emission, which are expressed as corresponding wavelengths in the units of nanometers, nm. For Rhodamine WT, the peak excitation occurs at 558 nm and the maximum emission is at 582 nm. Udenfriend (1962; p5-36) provides more in depth detail on the topic of the principles of fluorescence.

The concentration of fluorescent dye in a sample is determined using a fluorometer. In this study, a Turner model 10 Analog fluorometer was used for the first 24 experiments conducted on the Rossdale model and a Turner 10-AU fluorometer was used for all other experiments. Both of these fluorometers use filters to produce the wavelength of excitation for a particular tracer chemical and also to read the levels of light emitted by that tracer. A fluorometer reading gives a relative value for the radiant energy produced, which can then be related to the concentration of tracer chemical in the sample. Technical information on these two versions of the Model 10 fluorometer created by Turner Designs can be located in Udenfriend (1962, p37-95) and literature supplied by the manufacturer. The Turner 10-AU fluorometer is a newer digital version of the Model 10 Analog fluorometer. The 10-AU displays digital readings, which have automatically been adjusted by the appropriate concentration multiplier for ease of data recording. Each fluorometer has the ability to automatically select the appropriate sensitivity range for a particular concentration, and therefore measure a large range of concentrations. In drinking water, the detection limits can be as low as 0.01 μg/L and as high as approximately 100 μg/L.

Certain factors such as temperature, photochemical decay, pH, solvent background concentration, and fluorescent quenching can affect the accuracy of concentration measurements of Rhodamine WT (Udenfriend 1962; Smart and

Laidlaw 1977). These effects can be reduced or eliminated by using proper testing procedures. The most effective means of acquiring accurate results is to apply measurement techniques that are consistent for each sample. For example, the variance in readings, which can be attributed to temperature differences, can be minimised by measuring all samples at one common temperature. This variance can also be reduced during data analysis with the use of a temperature correction factor. Photochemical decay may occur if the dye is exposed to bright light, thereby reducing the dye concentration within the collected sample. To eliminate this effect, all samples should be stored in the absence of light. Rhodamine WT concentration is also affected by the pH level of the solvent. When the pH level is between 5 and 10, Rhodamine WT is considered stable (Smart and Laidlaw 1977; Wilson et al 1986). Drinking water will normally have a pH within this range, so the effects of pH have been disregarded in this study.

Rhodamine WT readings can be affected by the presence of other chemicals in the solvent. Two common causes are background fluorescence and quenching. The concentration reading for the tracer dye can be increased when the fluorescence levels in the solvent are similar to Rhodamine WT, causing background fluorescence. Although materials with similar fluorescence to Rhodamine WT are not normally found in drinking water, it is important to measure the background level before adding tracer dye to the basin. The background reading should then be subtracted from the sample readings during the analysis. Quenching is due to the presence of chemical compounds such as chlorine and oxygen, which over time, may reduce the concentration levels of Rhodamine WT (Wilson et al 1986). This can be avoided by analysing each sample immediately upon collection.

3.3 Experimental Procedures

The first step for each tracer test was to fill the reservoir model with city water and adjust the water level inside the basin using the constant head tank located at the outlet. The inflow was adjusted to the appropriate rate with the use of the two feeding line valves and by reading the discharge from the flowmeter also placed at the feeding line. The discharge was maintained at a constant value throughout the experiment. At this early stage in the experiment, the fluorometer was connected to its power source so that it would have ample time to warm-up.

The next step was to fill the jet tank with enough city water to supply the model for the duration of the experiment. Once full, a concentrated solution of the tracer chemical, Rhodamine WT was added to the jet tank. It was mixed carefully with the water to attain a uniform concentration inside the tank. Mixing was further improved by the re-circulation of tracer solution to the jet tank through a hose, which supplied the three circular jets entering the tank. Before introducing the tracer solution to the model, a sample was taken at three different positions within the jet tank to verify that the concentration was homogeneous. When the fluorometer readings for the three samples were within 5% of each other, it was assumed that the tank was well mixed. A sample was also collected from the reservoir model to test the concentration of background fluorescence within the storage basin. The reading for background concentration was recorded.

When the water level inside the reservoir was stable and the tracer solution in the jet tank was well mixed, the fresh water was shut off and the tracer solution in the jet tank was quickly supplied to the inlet(s) at the same specified discharge(s). Tracer solution that did not enter the model was re-circulated to the jet tank to maintain a sufficient degree of mixing throughout the experiment. The initial concentration measured at the inlet to the system ranged from approximately 60 to 100 ppb for the Rossdale model and 200 to 600 ppb for the E.L. Smith model.

Sampling was conducted by siphoning water from within the model through stainless steel tubes connected to vinyl tubing that had an inside diameter of 3.2 mm. Water was withdrawn using a 60 ml syringe and the samples were collected in 60 ml opaque, polyethylene bottles. The bottles were rinsed with clean water prior to each experiment to ensure that no residual fluorescence remained in the sample bottles. The model was also rinsed with fresh water between experiments to reduce any dye residuals, which could contribute to a background concentration.

For the Rossdale model, samples were collected periodically at the inlet, the intercell outlet and the outlet. Sampling for the E.L. Smith model occurred at two points: the inlet and the outlet. The samples in this study were measured immediately upon collection so that temperature changes were minimal. Each sample was transferred from its individual 60 ml bottle to a glass test tube, which was 100 mm long and had a 13 mm diameter. The test tube was only handled by its top edge and it was carefully wiped with a laboratory tissue before being placed inside the temperature control holder of the fluorometer. Once the dial reading stabilised, the level of fluorescence was recorded. As the same test tube was used for each test, it was rinsed with a small quantity of sample solution before the majority of the sample contents were transferred to the test tube.

A visualisation test was normally done prior to the first tracer test of each new configuration. The visualisation tests provided an estimate for the volume of water that would be required in the jet tank to conduct a complete tracer test. It also provided an estimation of the position of the tracer front at particular times during the experiment. This information was used to increase the amount of samples collected during relevant times of the tracer study. The sampling interval was decreased in response to a recommendation by Liem (1994) that the more

samples should be taken when the tracer is close to the estimated T_{10} value. The visualisation tests were conducted by introducing a red food colouring at the exit point of the jet tank via vinyl tubing and a stainless steel tube. For most of the visualisation tests, a purple-red dye called Cochineal A.P. Blend was used. The dye was composed of a cochineal extract in water with propylene glycol and potassium hydroxide, its specific gravity between 0.98 and 1.08. For reasons of availability, another dye called Liquicert Red R was used for the final Rossdale model configuration. It had a specific gravity of 1.05 and was composed of a dye known as FD & C Red #40.

3.4 Experimental Test Program

3.4.1 Nomenclature

The experimental test program was divided into two phases. The objective of the first phase was to determine that each physical model sufficiently represents the associated full-scale reservoir system. Then for the second phase of the study, modifications were made to the internal configuration of the models and the efficiency of each contact basin design was assessed using tracer tests and flow visualisation.

A nomenclature has been developed to identify each experiment in a format that is easily recognisable to the reader. The experiments are numbered in the order with which they were performed and each test name will include the first letter of the model name to distinguish it. For example, the first experiment performed on the Rossdale model will be referred to as R1 and the second experiment conducted in the E.L. Smith reservoir is called E2. The configurations will be labelled in a similar manner. Each configuration name will start with a C for configuration, followed by the first letter of the model name and then the configuration number. For example, CR1 refers to the first configuration of the Rossdale model and CE1

is the first configuration of the E.L. Smith model. This nomenclature will be applied to the subsequent tables and figures in this thesis.

3.4.2 Experiments in the Rossdale Model - Phase 1

Phase 1 of testing in the Rossdale storage basin model included twelve runs: R1 through R12. Table 3-2 summarises the details of the Rossdale model experiments. The first model configuration, CR1 is illustrated in Figure 3-6. Note that the inlet for CR1 is a circular jet entering the east cell. Experiments R1 to R5 were carried out using this arrangement. Experiments R1 and R2 were conducted with a water depth of 273 mm and a flow rate of 29.1 L/min, which is equivalent to a prototype depth of 7.2 m and discharge of 150 ML/d. The next test, R3 was completed at half the discharge rate. Experiment R4 and R5 mirrored the prototype values that were used for full-scale tracer studies conducted by Liem et al (1997). A prototype discharge of 150 ML/d with a water depth of 6.3 m, as well as a discharge of 130 ML/d with a depth of 5.8 m were used to test the prototype. Therefore, experiment R4 and R5 were performed at a model discharge of 29.1 L/min and depths of 239 mm and 220 mm, respectively.

The following configuration was adopted to observe whether or not the addition of columns in the model, which exist in the prototype, make a significant difference to the results. Circular sticks with a 20 mm diameter were added to the model to reflect the 460 mm diameter columns, which exist in the prototype. This modification was labelled as configuration CR2 and can be seen in Figure 3-7. Experiment R6 was performed at the same discharge and depth as experiment R4, so that the results could be compared. Photo Plate 3-3 includes both a view of the actual columns in the west cell of the prototype tank, and a view of the model with columns installed in it.

After the sixth experiment was completed, information was received from EPCOR Water Services regarding the actual post-construction configuration of the combined storage tanks. It was found that the first set of drawings that were obtained did not describe the real configuration of the reservoirs. The required alterations were performed, thereby leading to the third configuration of the model, CR3, which represents the actual existing layout. The modifications that resulted in the third configuration included a change to the inlet shape and the addition of a baffle wall to the west cell. The modified inlet consisted of a pipe elbow directing flow into a lowered section of the basin floor, as shown in Figure 3-3. Experiment R7 was run using configuration CR3 at a discharge of 29.1 L/min and a depth of 239 mm. For the following three experiments, the model flow rate was increased to 58.2 L/min, which corresponds to the maximum operational discharge of the Rossdale WTP. As mentioned earlier, when flows are greater than 150 ML/d, a portion of the water must enter through the west cell directly via the overflow inlet. Therefore, both Line #1 and Line #2 were opened to supply the tank for experiments R8, R9 and R10. A depth of 239 mm was utilised in experiments R8 and R10 and a depth of 265 mm was used in experiment R9.

The first set of construction drawings showed that the elevation of the existing baffle walls was less than the water level inside the tank for normal operation of the reservoir. For experiments R1 through R12, the baffle walls in the model were 190 mm high and the water level ranged from 167 mm to 273 mm. Further investigation within the prototype tanks revealed that the normal water level was below the height of the baffle walls. In order to see the effects of the baffle wall height on the tank performance, experiment R11 and R12 were conducted in CR3 with the water elevation lowered below the top of the baffle walls. The experiments were run at a discharge of 29.1 L/min and 23.5 L/min, respectively.

The first phase of the experimental test program for the combined reservoir model at the Rossdale WTP was completed with experiment R12.

3.4.3 Experiments in the Rossdale Model - Phase 2

There were a total of nineteen experiments performed for the second phase of testing on the Rossdale model. As mention previously, the objective of the second phase of experiments was to assess the impact of various distribution tank designs on the performance of the system. The modifications comprised mainly of changes to the internal configuration of the basins and to the inlet. The height of all baffle walls was increased to 350 mm above the basin floor, which is above the water elevation for all subsequent tests. The water is expected to be below the baffle walls for all actual prototype operational conditions.

The first modification to the existing layout at the Rossdale WTP consisted of moving the inlet and extensively altering the internal baffle wall configuration. It is labelled as configuration CR4 and its plan view diagram is included as Figure 3-8. One test, experiment R13 was performed on this design at a discharge of 29.1 L/min and with a water depth of 239 mm. Note that all subsequent experiments on the Rossdale model were operated using a depth of 239 mm.

Configuration CR5 had the same internal layout as CR4, with the exception of a diffuser pipe added to both the inlet and the intercell outlet. Figure 3-9 contains a diagram of the inlet diffuser and the intercell outlet diffuser installed in this configuration. The diffuser at the inlet for CR5 was a 750 mm long pipe with a 95 mm inside diameter. There were thirty holes, each with a 15 mm diameter, spaced at 18 mm centre to centre, and cut in one row along the length of the diffuser. The diffuser that was located at the intercell outlet had a inside diameter of 95 mm and a length of 800 mm. It shared the same pattern of holes as the inlet diffuser. Both diffusers had an open area of 5300 mm^2 and were added as an

attempt to decrease the momentum in the flow. Experiment R14 was performed on CR5 at a flow rate of 29.1 L/min.

Experiments R15 through R18 were performed to examine configuration CR6. The sixth configuration was a modification of CR5. Changes were made to the baffle configuration in the west cell. Because of alterations to the baffle arrangement, limited space was available for the diffuser pipe at the intercell outlet. A new diffuser pipe was installed. It had the same inside diameter of 95 mm but its length was decreased to 405 mm. Two rows of 15 mm diameter holes were cut along its length and spaced at 18 mm centre to centre both horizontally and vertically. It had an open area of 7245 mm^2 for the passage of flow. There was also a 3 mm thick steel plate installed inside the diffuser with an open area of 5320 mm^2. The plate was added in an attempt to further decrease the momentum of flow. It had fourteen 22 mm diameter holes cut in the pattern shown in Figure 3-9. The diffuser at the inlet of CR6 was the same used in CR5. Figure 3-10 is a plan view diagram of CR6. A number of different flow rates were applied for the examination of this configuration. Experiment R15 was performed at the most common flow rate for this study, 29.1 L/min. Experiment R16, R17, and R18 were conducted at a discharge of 9.7 L/min, 48.5 L/min and 38.8 L/min, respectively.

The following four experiments were performed on configuration CR7, which can be seen as a plan view diagram in Figure 3-11. Configuration CR7 is similar to CR6, but has additional baffle walls in the east cell and a different flow diffuser installed at the inlet. The inlet diffuser was 570 mm long with thirty 15 mm diameter holes cut in one row along its length. The combined area of the diffuser outlet holes was 5300 mm^2. The inlet diffuser contained a metal plate with an open area of 8745 mm^2. Experiments R19 and R21 were run at a 29.1 L/min

discharge and experiments R20 and R22 were tested at flow rates of 58.2 L/min and 38.8 L/min, respectively.

In configuration CR8, the diffusers in CR7 were replaced with another set of flow diffusers. Both the inlet and intercell outlet diffusers were 405 mm in length and had the same pattern of exit holes, as illustrated in Figure 3-9. Experiment R23 was conducted at 29.1 L/min.

In the next configuration, CR9 the existing layout of the east cell, which was initially tested in CR3, was referred to as a basis for making modifications. Configuration CR9 had the same layout as CR3 except that the centre baffle wall of CR3 was extended to a length of 3820 mm (model) and a 485 mm long baffle wall was added near the east end of that centre baffle. The inlet for CR9 was located where the intercell outlet had been located in CR3. The inlet was comprised of a 50 mm diameter inlet pipe with a 545 mm long diffuser pipe attachment. There were four 35 mm diameter holes along the diffuser pipe and the openings faced the west wall of the cell. A schematic of CR9 is included as Figure 3-12. Experiments R24 and R25 were performed exclusively on the east cell of CR9. A discharge of 41.7 L/min was used for experiment R24 and a discharge of 58.2 L/min was used for experiment R25.

The east cell of configuration CR10 has a similar layout to CR9 except for the absence of the small baffle wall at the east end of the cell. The west cell of CR10 contains a serpentine formation of baffle walls as illustrated in Figure 3-13. The inlet for CR10 was the same installation used in CR9, and the outlet was the same as for all previous configurations. The passage of flow from the east cell to the west cell in CR10 is distinct from previous arrangements. In this configuration, there are two intercell outlets leading from the east cell to the west cell. The two intercell outlets will be referred to as the north intercell outlet and the south

intercell outlet. The north intercell outlet started at a hole on the west end of the centre baffle wall. The intercell outlet continued into a 70 mm diameter pipe that followed along the wall, which separates the two cells. The pipe then connected to a pipe elbow that led into the west cell. The south intercell outlet is the same 50 mm diameter pipe-elbow that was used as the inlet to the existing configuration. The elbow connection joined to a 60 mm pipe, which led to a 900 mm long diffuser. The diffuser had three 35 mm diameter holes with a centre to centre spacing of 240 mm. Configuration CR10 was tested at a flow rate of 58.2 L/min in experiment R26.

Configuration CR11 had the same layout as configuration CR10, except that the diameter of the holes in both diffuser pipes was increased from 35 mm to 45 mm. Increasing the size of the exit holes in the diffuser pipe was done in an effort to reduce the velocity of the water exiting these pipes. The configuration with larger diffuser pipe outlets is referred to as CR11. For this design, there were three tests performed. The first two experiments, R27 and R28 were conducted with a discharge of 58.2 L/min and the third test, experiment R29 was conducted at a flow rate of 29.1 L/min.

The last two experiments for the Rossdale model were performed on the final configuration, CR12. The last design had no diffusers and less piping than the preceding arrangement. The baffle walls were arranged in a similar manner to CR11, but an additional baffle wall was installed in each cell. Configuration CR12 is illustrated in Figure 3-14. Experiment R30 was performed with a discharge of 58.2 L/min and experiment R31 used a discharge of 29.1 L/min.

3.4.4 Experiments in the E.L. Smith Model - Phase 1

There were five experiments conducted in phase 1 of the E.L. Smith reservoir study. All five experiments were performed using the existing configuration at the

E.L. Smith WTP. The existing layout has been described earlier in this chapter and a plan view diagram of the model is provided as Figure 3-5. Experiment E1 was conducted at the maximum allowable discharge for the plant, which is 250ML/d prototype and 11.2 L/min model. The water depth used for experiment E1 was 89 mm. The following four experiments of phase 1 were operated at discharge and depth values that correspond to those used in the two full-scale tracer tests completed by Liem et al (1997). The first test performed by Liem et al (1997) was operated at a discharge of 230 ML/d and a depth of 3.9 m, which scale down to model values of 10.3 L/min and 82 mm, respectively. Experiment E2 and E5 were run under these operating conditions. The second test was conducted at a discharge of 180 ML/d and a depth of 4.1 m, which are equivalent to a flow rate of 8.1 L/min and a depth of 86 mm in the model. Experiments E3 and E4 were performed at this second condition. Table 3-3 summarises the details of the experiments conducted in the E.L. Smith model.

3.4.5 Experiments in the E.L. Smith Model - Phase 2

The first modification to the existing reservoir was the addition of four baffle walls, two placed on either side of the existing centre baffle. The outlet was moved to a position 110 mm from the side wall of the basin to accommodate for the new baffles. A plan view diagram CE2 is included as Figure 3-15. Experiments E6 to E9 were performed on this configuration. Experiments E6 and E7 were executed using a discharge of 10.3 L/min and a depth of 82 mm while experiments E8 and E9 were conducted with a discharge of 8.1 L/min and depth of 86 mm. Two tests were run for each operating condition to confirm the results.

The second modification entailed the addition of another four baffle walls as shown in Figure 3-16. This configuration, CE3 was tested in the same manner as the one before it. Experiments E10 and E11 were performed at a flow rate of 10.3 L/min and experiments E12 and E13 were performed at a discharge of

8.1 L/min. Both discharges were paired with the appropriate depth as in all previous tests of the E.L. Smith model.

Table 3-1. Prototype to Model Scale Factors

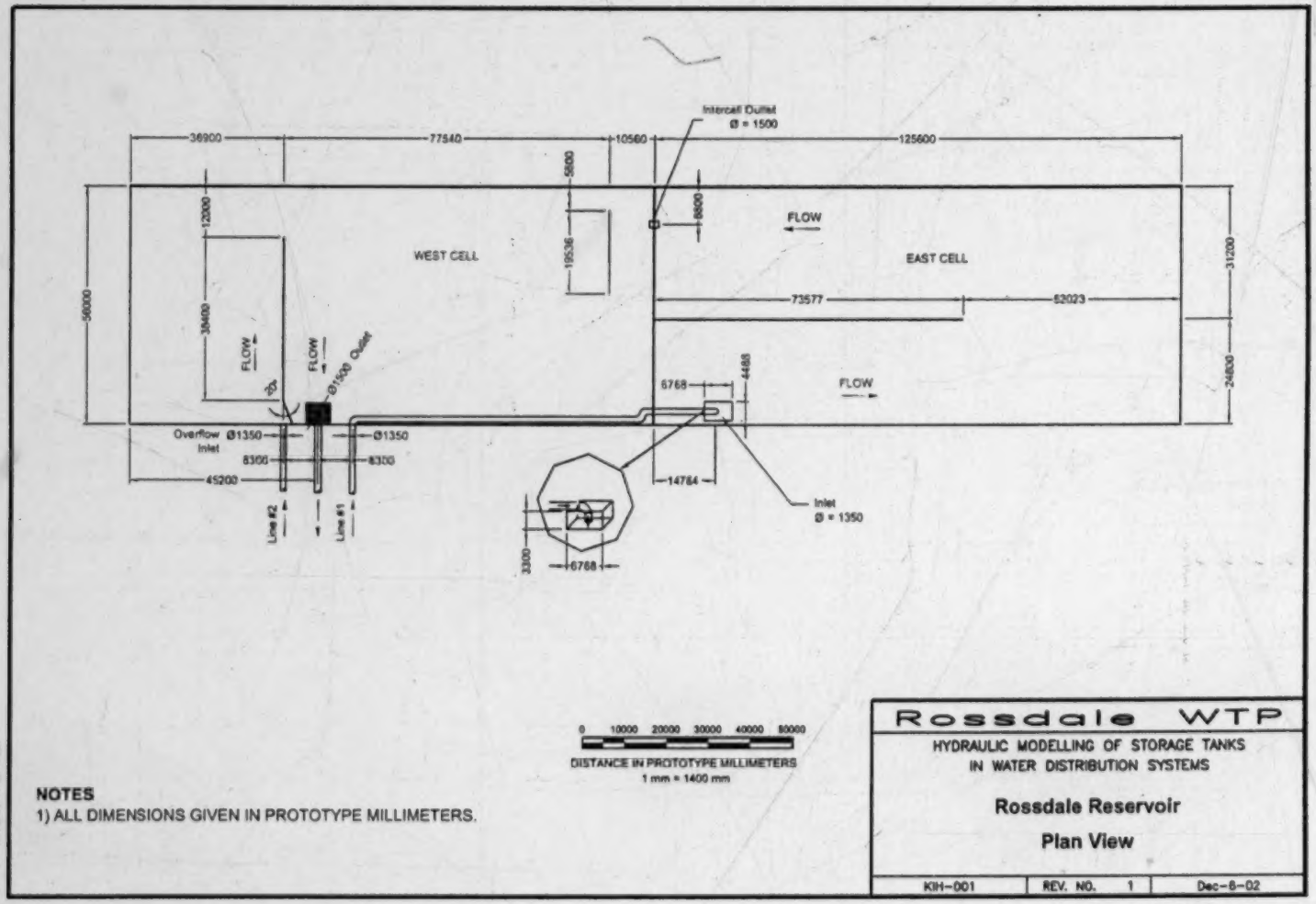
Parameter	Relation	Rossdale WTP Scale Factors	E.L. Smith WTP Scale Factors
Length	λ	26.4	47.46
Area	λ^2	697	2252
Volume	λ^3	18400	106901
Time	$\lambda^{0.5}$	5.14	6.89
Velocity	$\lambda^{0.5}$	5.14	6.89
Discharge	$\lambda^{2.5}$	3581	15517

Table 3-2. Summary of the Rossdale Model Test Program

Configuration (1)	Experiment # (2)	Qm (L/min) (3)	Depth (mm) (4)
Phase 1: Model Confirmation			
CR1	R1	29.1	273
	R2	29.1	273
	R3	14.5	273
	R4	29.1	239
	R5	29.1	220
CR2	R6	29.1	239
CR3	R7	29.1	239
	R8	58.2	239
	R9	58.2	265
	R10	58.2	239
	R11	29.1	167
	R12	23.5	174
Phase 2: Design Modifications			
CR4	R13	29.1	239
CR5	R14	29.1	239
CR6	R15	29.1	239
	R16	9.7	239
	R17	48.5	239
	R18	38.8	239
CR7	R19	29.1	239
	R20	58.2	239
	R21	29.1	239
	R22	38.8	239
CR8	R23	29.1	239
CR9	R24	41.7	239
	R25	58.2	239
CR10	R26	58.2	239
CR11	R27	58.2	239
	R28	58.2	239
	R29	29.1	239
CR12	R30	58.2	239
	R31	29.1	239

Table 3-3. Summary of the E.L Smith Model Test Program

Configuration (1)	Experiment # (2)	Qm (L/min) (3)	Depth (mm) (4)
Phase 1: Model Confirmation			
CE1	E1	11.2	89
	E2	10.3	82
	E3	8.1	86
	E4	8.1	86
	E5	10.3	82
Phase 2: Design Modifications			
CE2	E6	10.3	82
	E7	10.3	82
	E8	8.1	86
	E9	8.1	86
CE3	E10	10.3	82
	E11	10.3	82
	E12	8.1	86
	E13	8.1	86



NOTES
1) ALL DIMENSIONS GIVEN IN PROTOTYPE MILLIMETERS.

Rossdale WTP

HYDRAULIC MODELLING OF STORAGE TANKS
IN WATER DISTRIBUTION SYSTEMS

Rossdale Reservoir

Plan View

KIH-001	REV. NO. 1	Dec-6-02

FIGURE 3-1

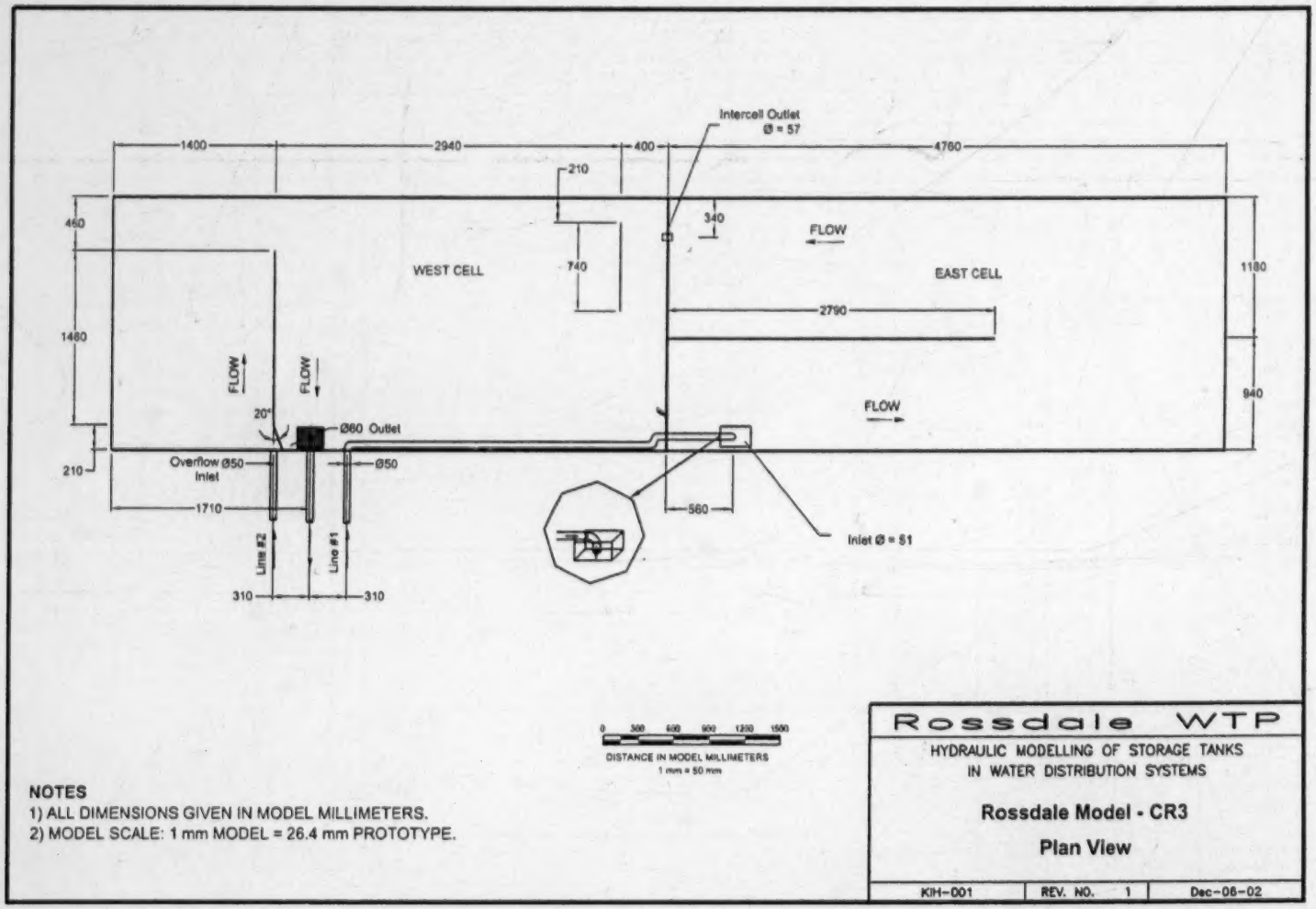
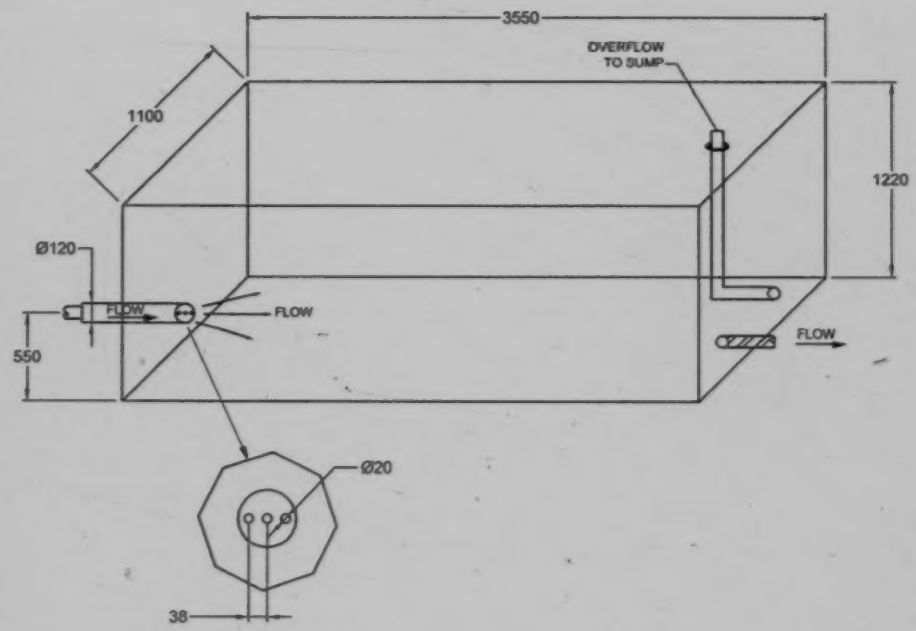
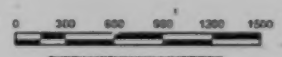

Intercell Outlet
Ø = 57
1400
2940
400
4760
210
460
340
FLOW
WEST CELL
740
EAST CELL
1180
2790
1480
FLOW
FLOW
940
FLOW
20°
Ø60 Outlet
210
Overflow Ø50
Inlet
Ø50
1710
560
Inlet Ø = 51
Line #2
Line #1
310
310
0 300 600 900 1200 1500
DISTANCE IN MODEL MILLIMETERS
1 mm = 50 mm
NOTES
1) ALL DIMENSIONS GIVEN IN MODEL MILLIMETERS.
2) MODEL SCALE: 1 mm MODEL = 26.4 mm PROTOTYPE.
Rossdale WTP
HYDRAULIC MODELLING OF STORAGE TANKS
IN WATER DISTRIBUTION SYSTEMS
Rossdale Model - CR3
Plan View
KIH-001
REV. NO. 1
Dec-06-02

FIGURE 3-2





NOTES
1) ALL DIMENSIONS GIVEN IN MILLIMETERS.
2) JET TANK CONTAINS A MIXTURE OF WATER AND TRACER CHEMICAL.

T. Blench Hydraulics Laboratory		
HYDRAULIC MODELLING OF STORAGE TANKS IN WATER DISTRIBUTION SYSTEMS		
Jet Tank		
KIH–001	REV. NO. 0	Dec–06–02

FIGURE 3-3

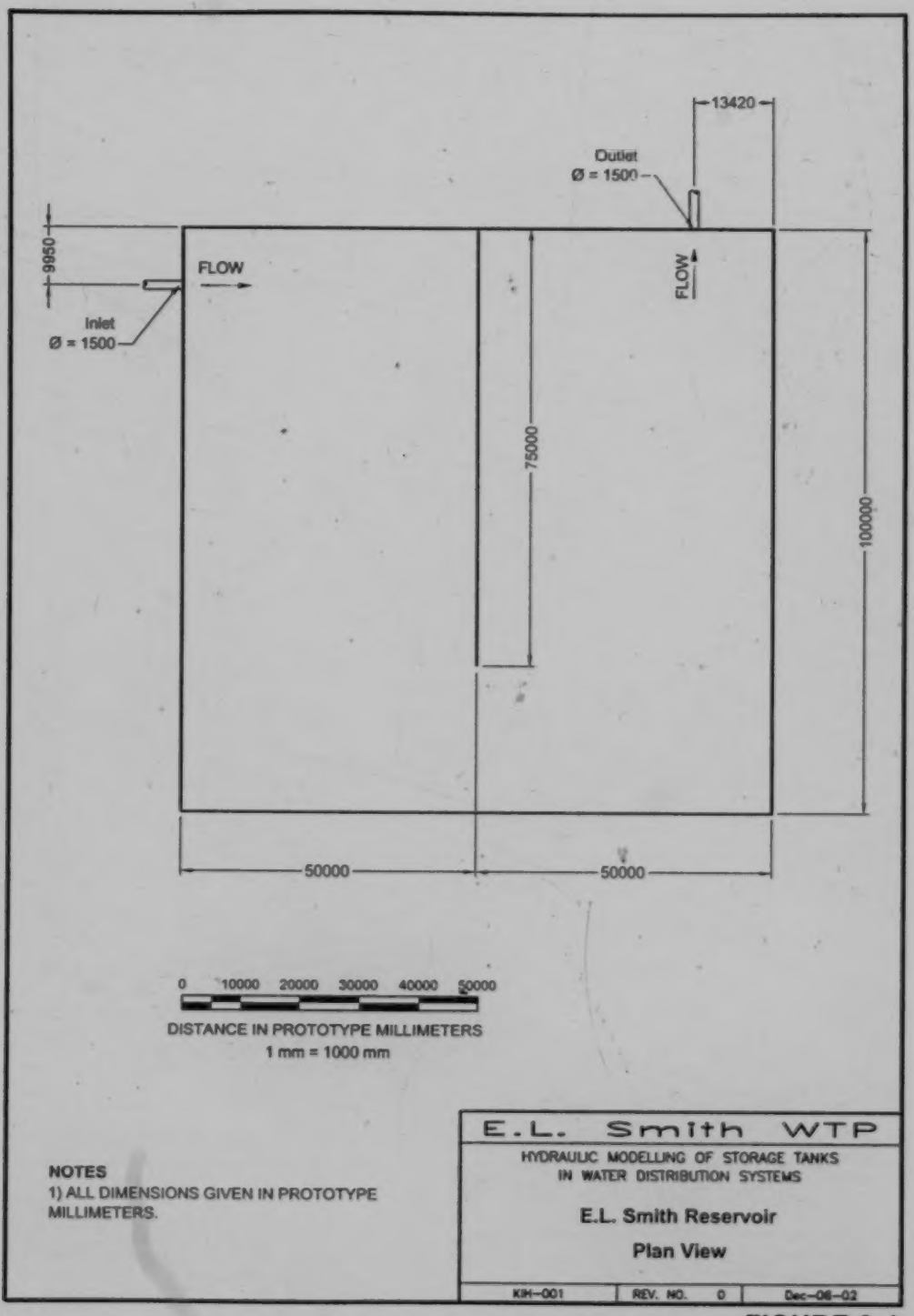

13420
Outlet
Ø = 1500
9950
FLOW
Inlet
Ø = 1500
FLOW
75000
100000
50000
50000
0 10000 20000 30000 40000 50000
DISTANCE IN PROTOTYPE MILLIMETERS
1 mm = 1000 mm
NOTES
1) ALL DIMENSIONS GIVEN IN PROTOTYPE MILLIMETERS.
E.L. Smith WTP
HYDRAULIC MODELLING OF STORAGE TANKS IN WATER DISTRIBUTION SYSTEMS
E.L. Smith Reservoir
Plan View
KIH-001
REV. NO. 0
Dec-06-02

FIGURE 3-4

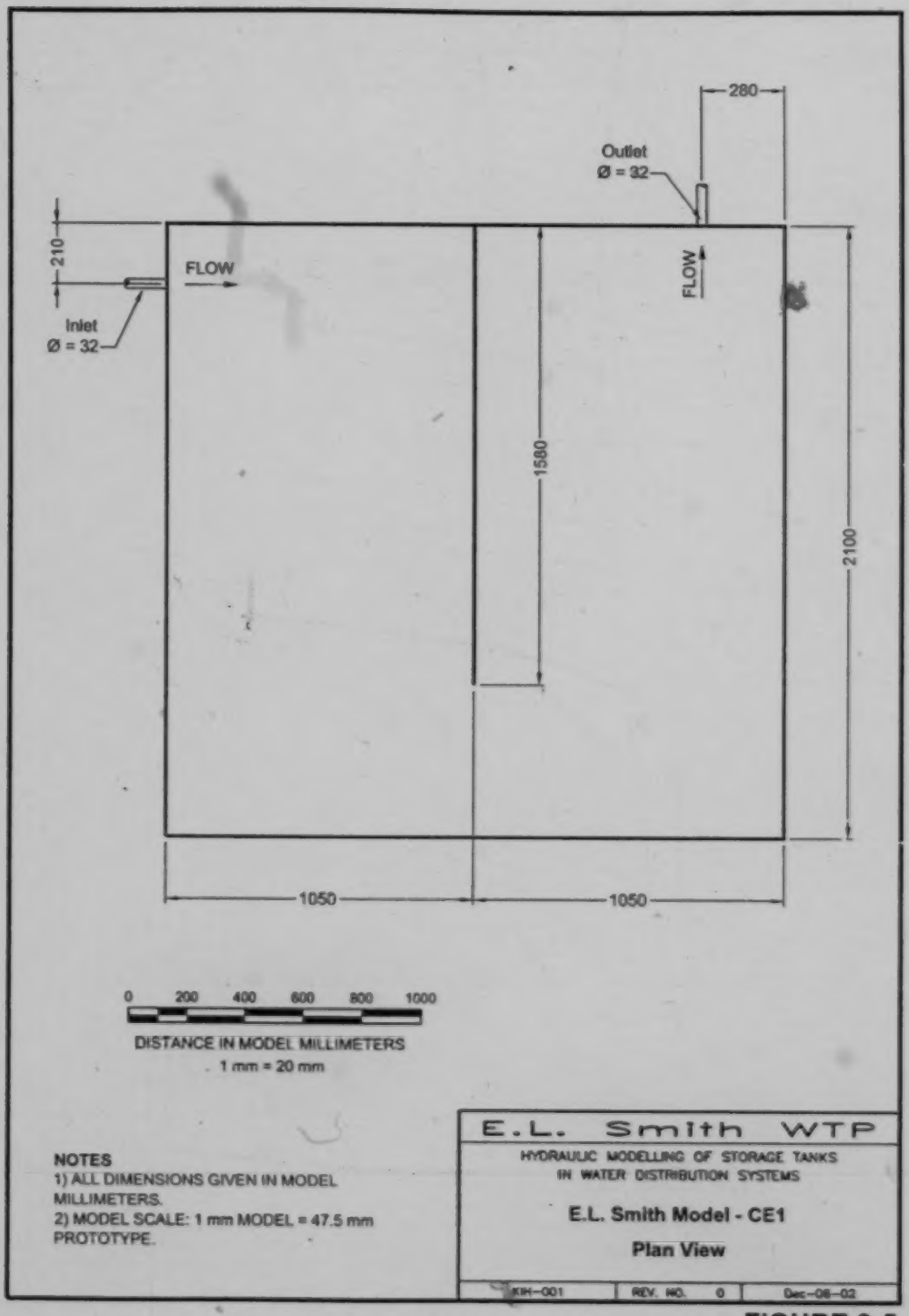

280
Outlet
Ø = 32
210
FLOW
FLOW
Inlet
Ø = 32
1580
2100
1050
1050
0 200 400 600 800 1000
DISTANCE IN MODEL MILLIMETERS
1 mm = 20 mm
NOTES
1) ALL DIMENSIONS GIVEN IN MODEL MILLIMETERS.
2) MODEL SCALE: 1 mm MODEL = 47.5 mm PROTOTYPE.
E.L. Smith WTP
HYDRAULIC MODELLING OF STORAGE TANKS IN WATER DISTRIBUTION SYSTEMS
E.L. Smith Model - CE1
Plan View
KIH-001
REV. NO. 0
Dec-06-02

FIGURE 3-5

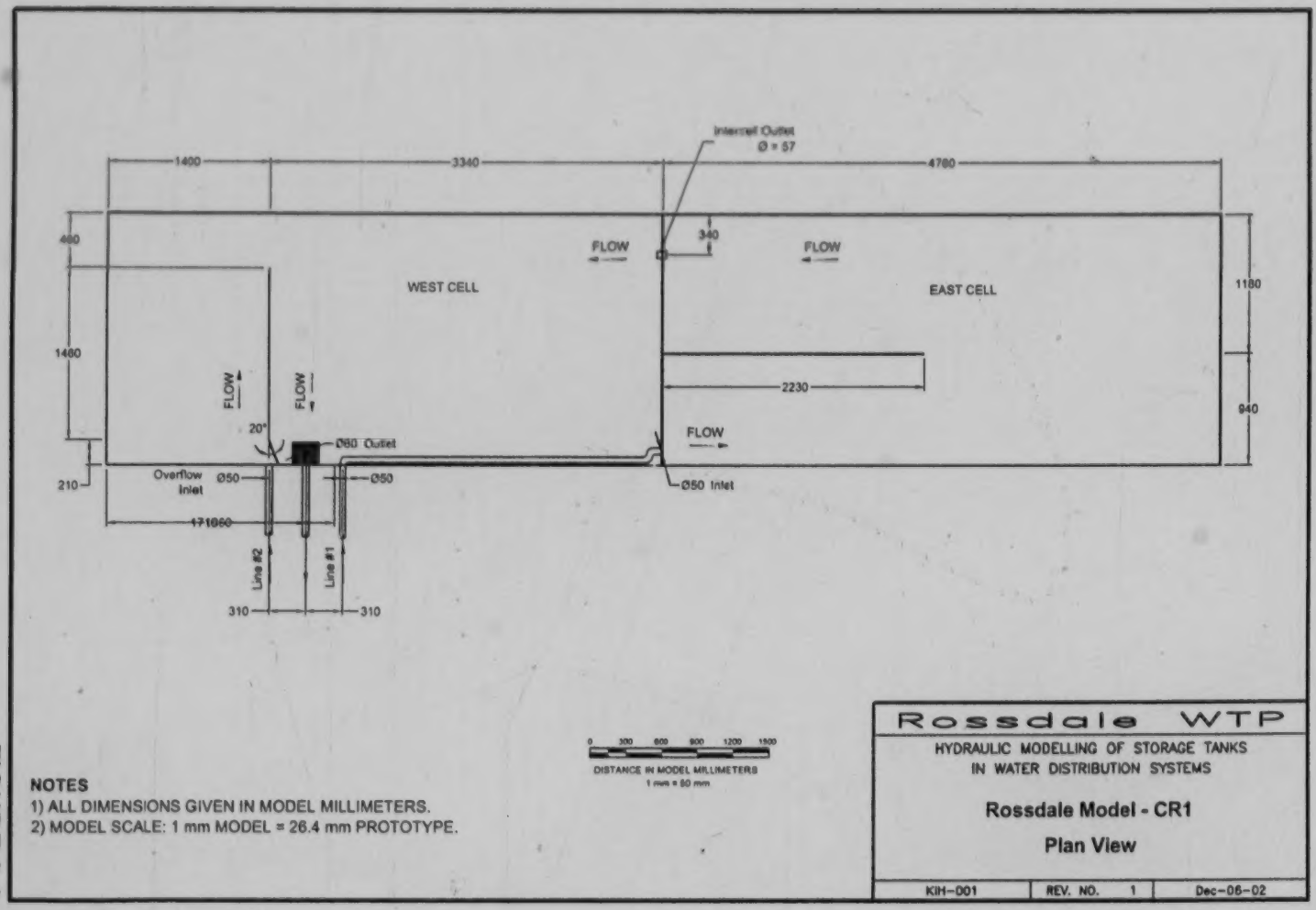

Intercell Outlet
Ø = 57
1400
3340
4780
400
340
FLOW
FLOW
WEST CELL
EAST CELL
1180
1460
2230
940
FLOW
FLOW
20°
Ø60 Outlet
FLOW
210
Overflow Inlet
Ø50
Ø50
Ø50 Inlet
1960
Line #2
Line #1
310
310
0 300 600 900 1200 1500
DISTANCE IN MODEL MILLIMETERS
1 mm = 50 mm
NOTES
1) ALL DIMENSIONS GIVEN IN MODEL MILLIMETERS.
2) MODEL SCALE: 1 mm MODEL = 26.4 mm PROTOTYPE.
Rossdale WTP
HYDRAULIC MODELLING OF STORAGE TANKS
IN WATER DISTRIBUTION SYSTEMS
Rossdale Model - CR1
Plan View
KIH-001
REV. NO. 1
Dec-06-02

FIGURE 3-6

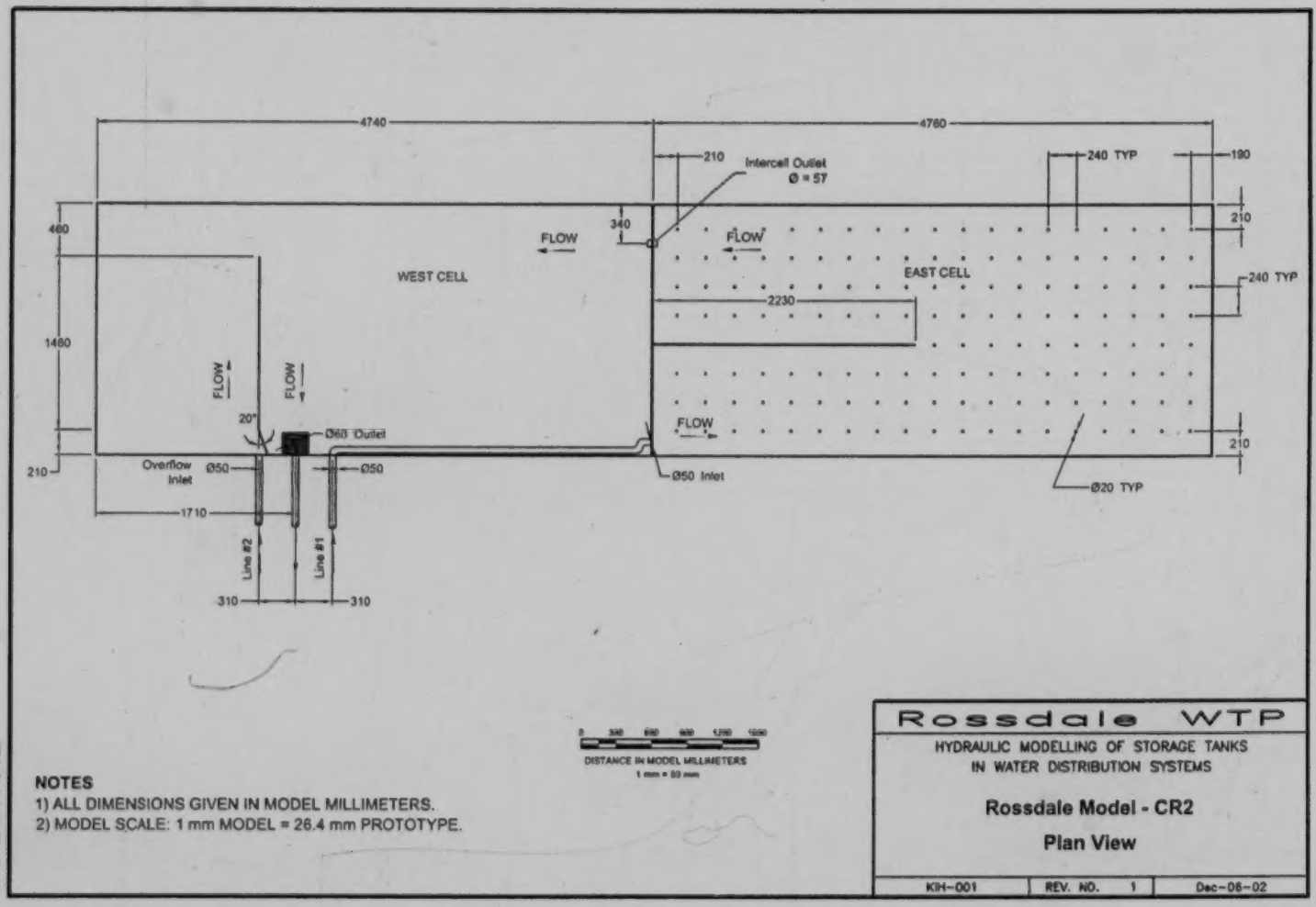

4740
4760
210
Intercell Outlet
Ø = 57
240 TYP
190
460
340
FLOW
FLOW
210
WEST CELL
EAST CELL
240 TYP
2230
1480
FLOW
FLOW
20°
Ø60 Outlet
FLOW
210
Overflow
Inlet
Ø50
Ø50
Ø50 Inlet
Ø20 TYP
1710
Line #2
Line #1
310
310
DISTANCE IN MODEL MILLIMETERS
1 mm = 53 mm
NOTES
1) ALL DIMENSIONS GIVEN IN MODEL MILLIMETERS.
2) MODEL SCALE: 1 mm MODEL = 26.4 mm PROTOTYPE.
Rossdale WTP
HYDRAULIC MODELLING OF STORAGE TANKS
IN WATER DISTRIBUTION SYSTEMS
Rossdale Model - CR2
Plan View
KIH-001
REV. NO. 1
Dec-06-02

FIGURE 3-7

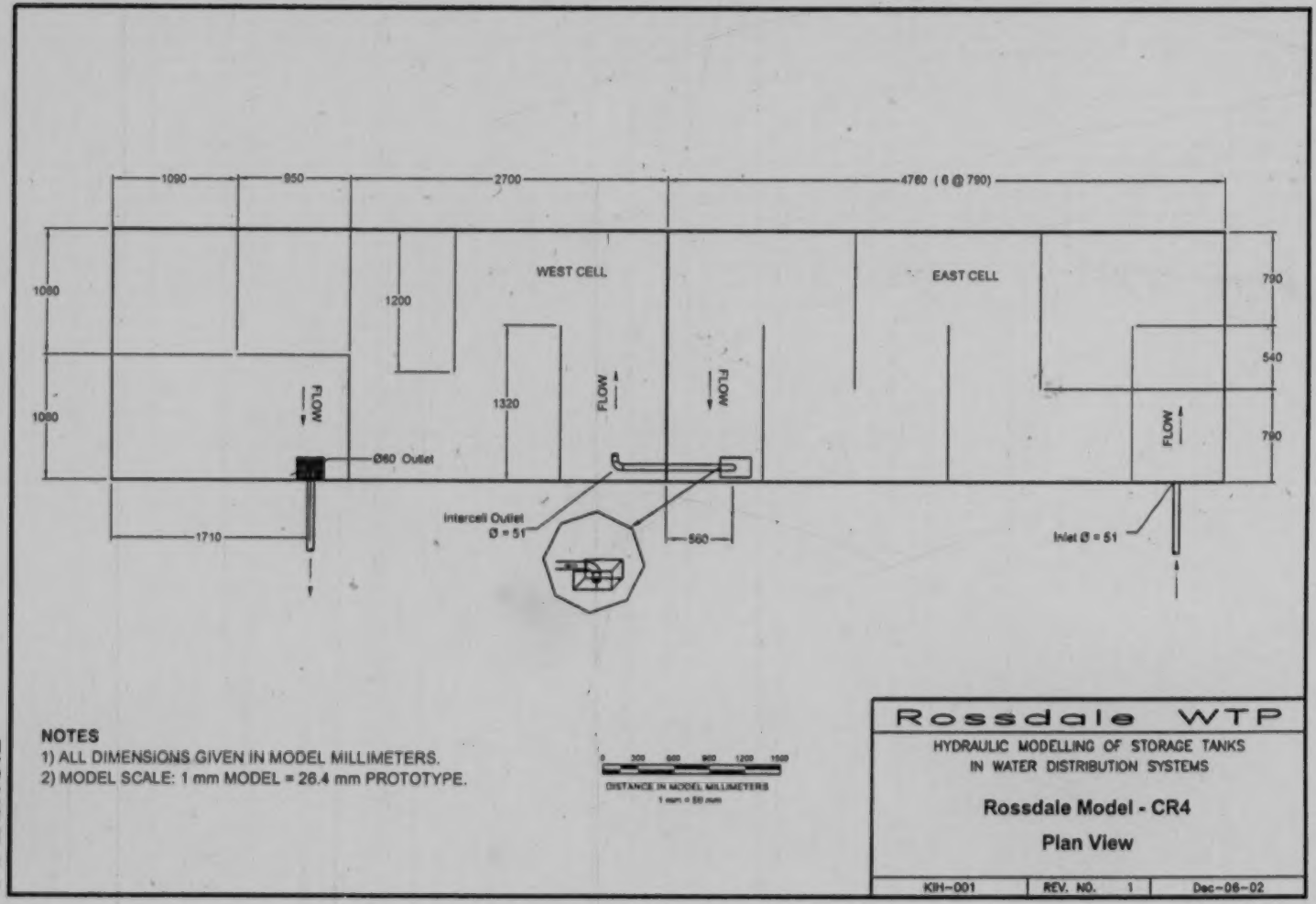

1090
950
2700
4760 (6 @ 790)
1080
1080
1200
1320
WEST CELL
EAST CELL
790
540
790
FLOW
FLOW
FLOW
FLOW
Ø60 Outlet
Intercell Outlet
Ø = 51
Inlet Ø = 51
1710
560
NOTES
1) ALL DIMENSIONS GIVEN IN MODEL MILLIMETERS.
2) MODEL SCALE: 1 mm MODEL = 26.4 mm PROTOTYPE.
0 300 600 900 1200 1500
DISTANCE IN MODEL MILLIMETERS
Rossdale WTP
HYDRAULIC MODELLING OF STORAGE TANKS
IN WATER DISTRIBUTION SYSTEMS
Rossdale Model - CR4
Plan View
KIH-001
REV. NO. 1
Dec-06-02

FIGURE 3-8

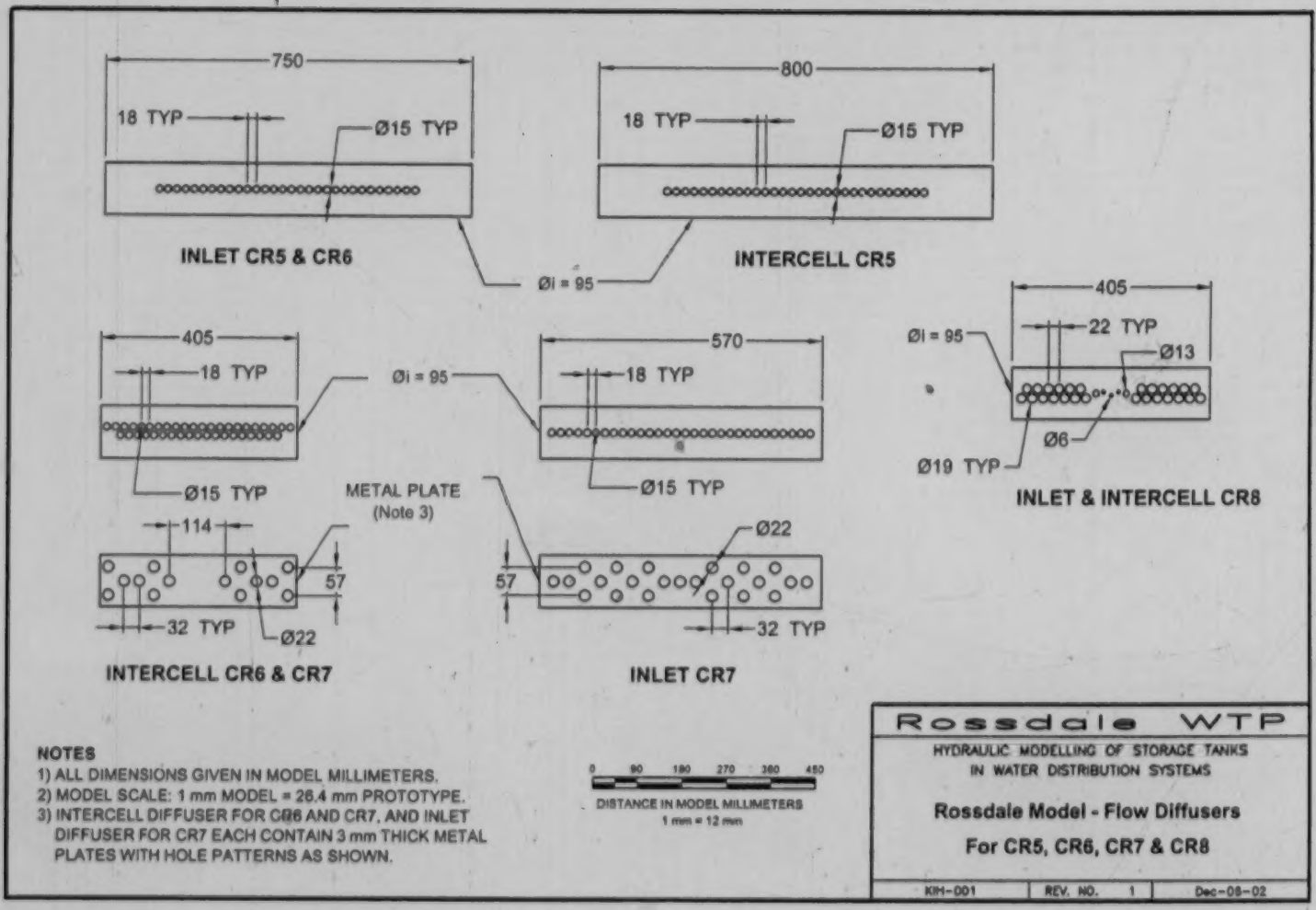
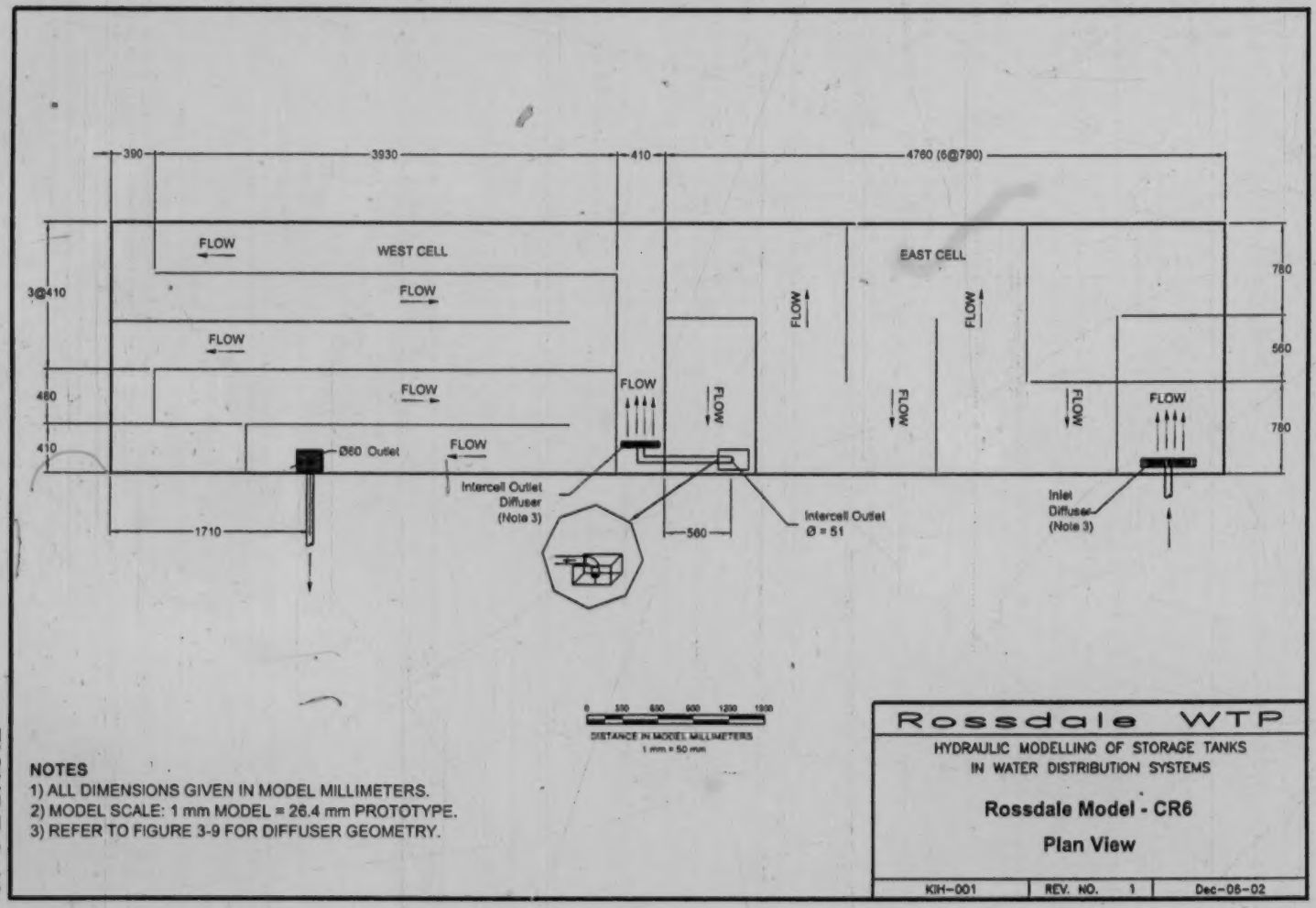

750
18 TYP
Ø15 TYP
INLET CR5 & CR6
Øi = 95
800
18 TYP
Ø15 TYP
INTERCELL CR5
405
18 TYP
Ø15 TYP
Øi = 95
570
18 TYP
Ø15 TYP
METAL PLATE
(Note 3)
114
57
32 TYP
Ø22
INTERCELL CR6 & CR7
57
Ø22
32 TYP
INLET CR7
405
22 TYP
Ø13
Øi = 95
Ø6
Ø19 TYP
INLET & INTERCELL CR8
NOTES
1) ALL DIMENSIONS GIVEN IN MODEL MILLIMETERS.
2) MODEL SCALE: 1 mm MODEL = 26.4 mm PROTOTYPE.
3) INTERCELL DIFFUSER FOR CR6 AND CR7, AND INLET DIFFUSER FOR CR7 EACH CONTAIN 3 mm THICK METAL PLATES WITH HOLE PATTERNS AS SHOWN.
0 90 180 270 360 450
DISTANCE IN MODEL MILLIMETERS
1 mm = 12 mm
Rossdale WTP
HYDRAULIC MODELLING OF STORAGE TANKS IN WATER DISTRIBUTION SYSTEMS
Rossdale Model - Flow Diffusers
For CR5, CR6, CR7 & CR8
KIH-001
REV. NO. 1
Dec-08-02

FIGURE 3-9



NOTES
1) ALL DIMENSIONS GIVEN IN MODEL MILLIMETERS.
2) MODEL SCALE: 1 mm MODEL = 26.4 mm PROTOTYPE.
3) REFER TO FIGURE 3-9 FOR DIFFUSER GEOMETRY.

Rossdale WTP

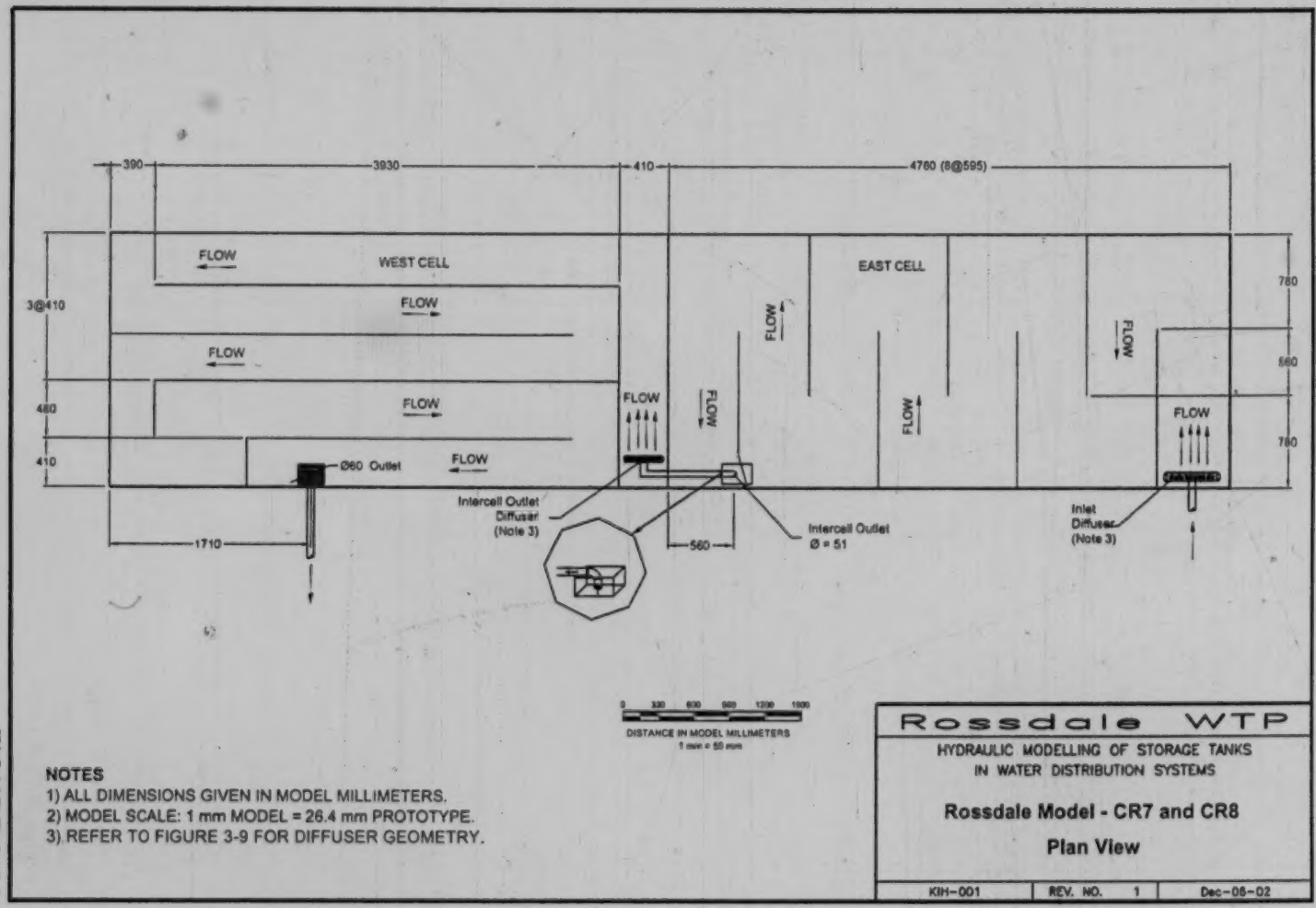
HYDRAULIC MODELLING OF STORAGE TANKS
IN WATER DISTRIBUTION SYSTEMS

Rossdale Model - CR6

Plan View

KIH-001	REV. NO. 1	Dec-06-02

FIGURE 3-10



NOTES
1) ALL DIMENSIONS GIVEN IN MODEL MILLIMETERS.
2) MODEL SCALE: 1 mm MODEL = 26.4 mm PROTOTYPE.
3) REFER TO FIGURE 3-9 FOR DIFFUSER GEOMETRY.

FIGURE 3-11

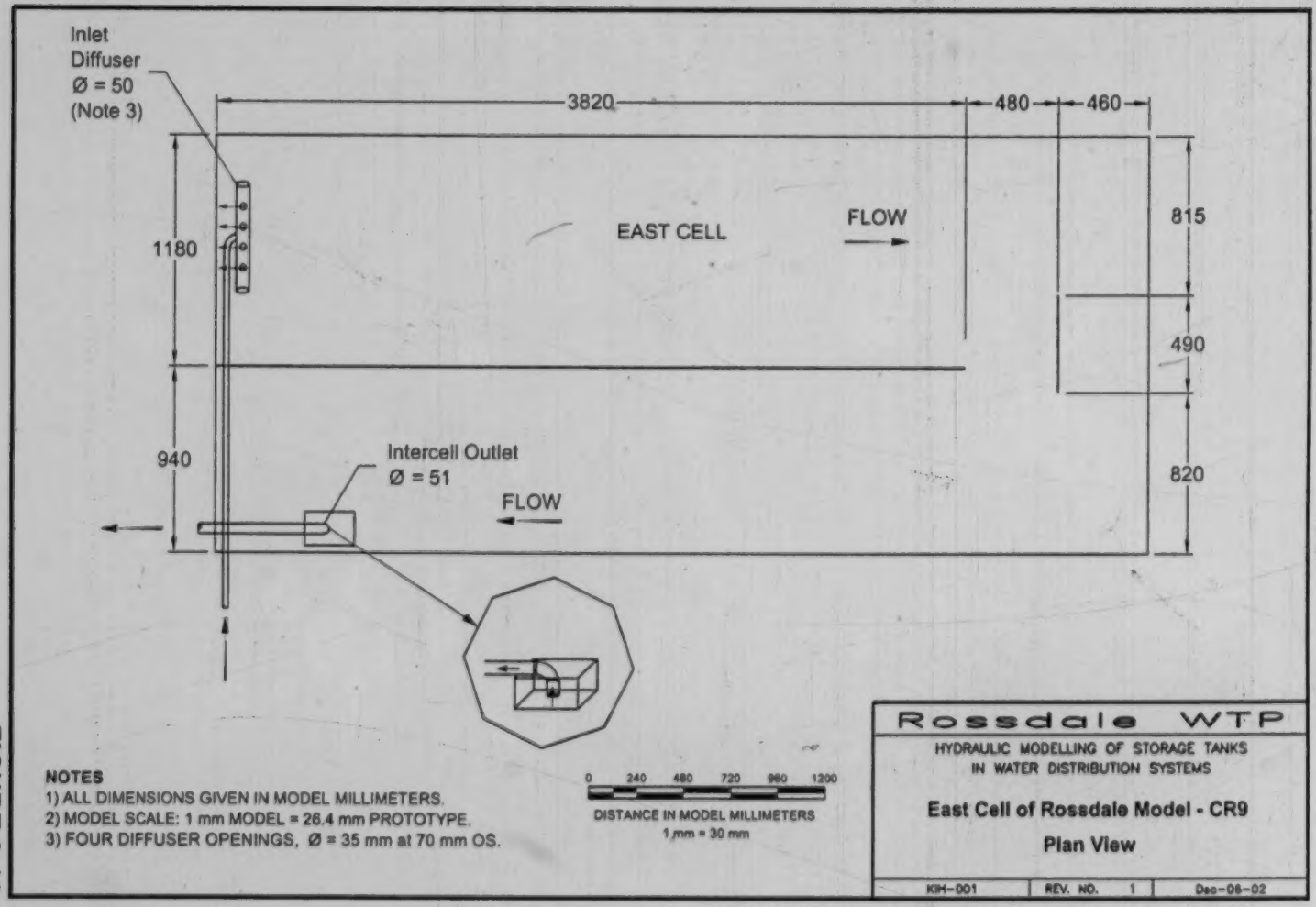
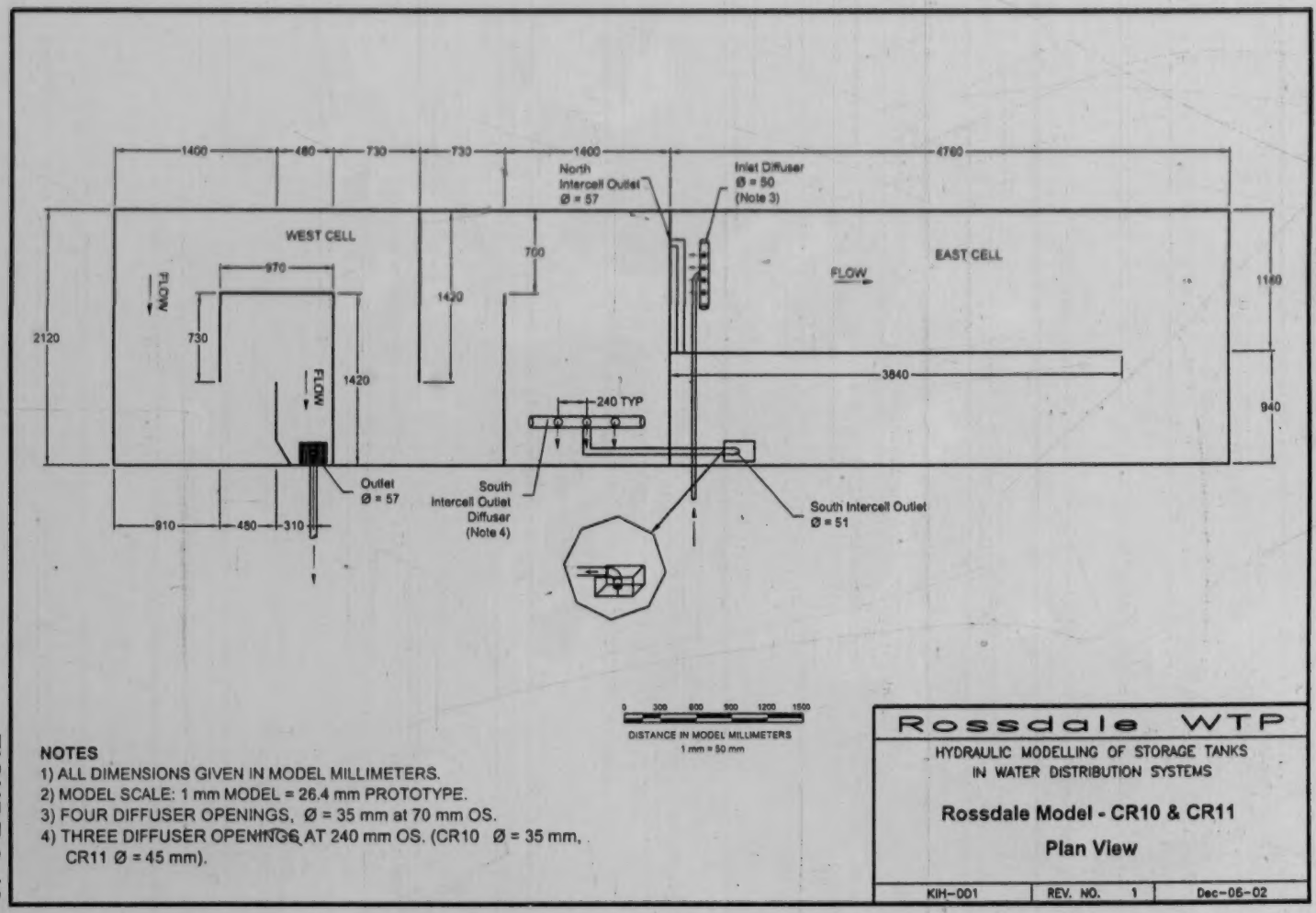

Inlet
Diffuser
Ø = 50
(Note 3)
3820
480
460
1180
EAST CELL
FLOW
815
490
940
Intercell Outlet
Ø = 51
FLOW
820
NOTES
1) ALL DIMENSIONS GIVEN IN MODEL MILLIMETERS.
2) MODEL SCALE: 1 mm MODEL = 26.4 mm PROTOTYPE.
3) FOUR DIFFUSER OPENINGS, Ø = 35 mm at 70 mm OS.
0 240 480 720 960 1200
DISTANCE IN MODEL MILLIMETERS
1 mm = 30 mm
Rossdale WTP
HYDRAULIC MODELLING OF STORAGE TANKS
IN WATER DISTRIBUTION SYSTEMS
East Cell of Rossdale Model - CR9
Plan View
KIH-001
REV. NO. 1
Dec-06-02

FIGURE 3-12



NOTES

1) ALL DIMENSIONS GIVEN IN MODEL MILLIMETERS.
2) MODEL SCALE: 1 mm MODEL = 26.4 mm PROTOTYPE.
3) FOUR DIFFUSER OPENINGS, Ø = 35 mm at 70 mm OS.
4) THREE DIFFUSER OPENINGS AT 240 mm OS. (CR10 Ø = 35 mm, CR11 Ø = 45 mm).

Rossdale WTP		
HYDRAULIC MODELLING OF STORAGE TANKS IN WATER DISTRIBUTION SYSTEMS		
Rossdale Model - CR10 & CR11		
Plan View		
KIH-001	REV. NO. 1	Dec-06-02

FIGURE 3-13

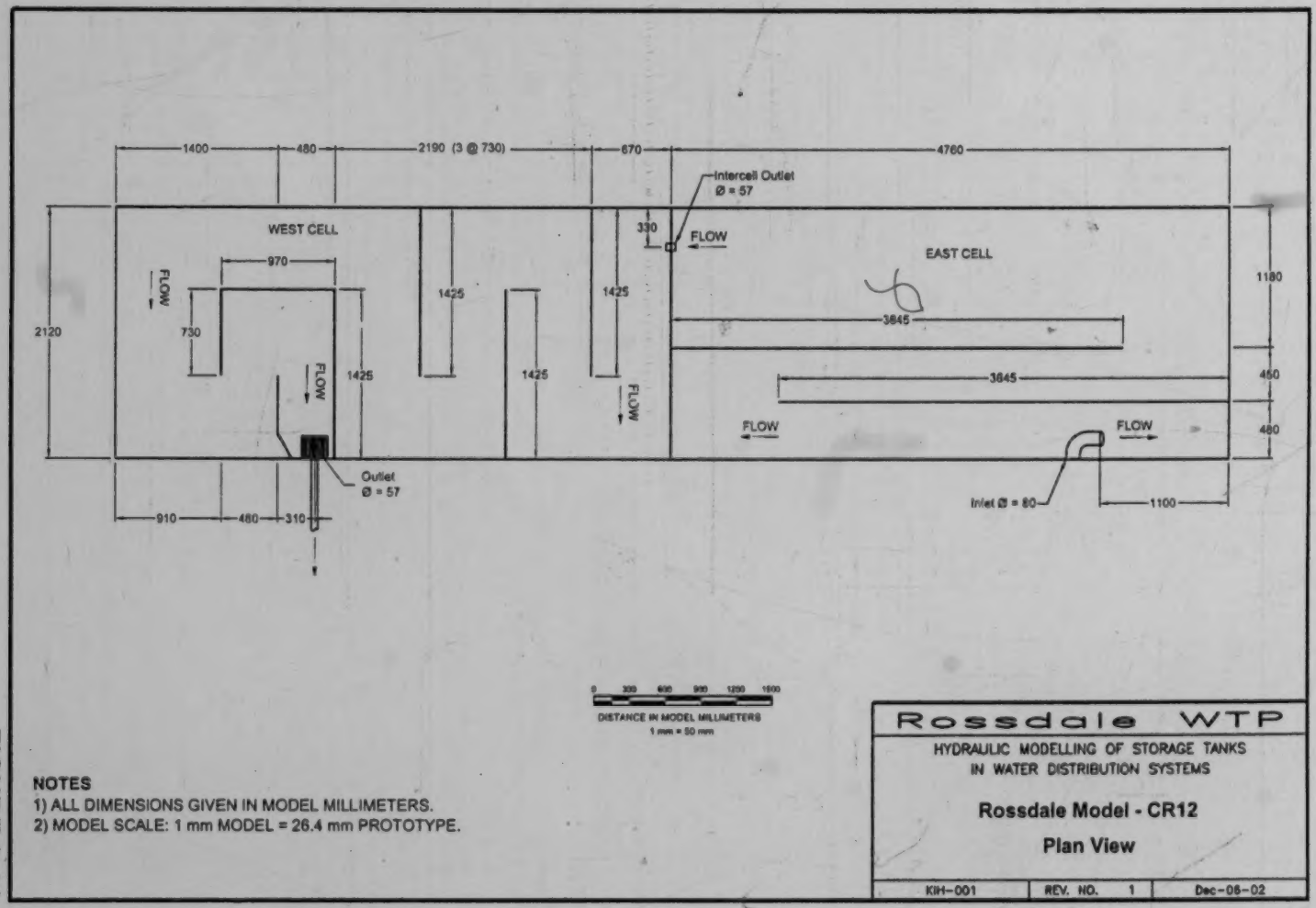

1400
480
2190 (3 @ 730)
670
4760
Intercell Outlet
Ø = 57
WEST CELL
EAST CELL
330
FLOW
970
730
2120
1425
1425
1425
1425
3845
3845
1180
450
480
1100
910
480
310
Outlet
Ø = 57
Inlet Ø = 80
DISTANCE IN MODEL MILLIMETERS
1 mm = 50 mm
NOTES
1) ALL DIMENSIONS GIVEN IN MODEL MILLIMETERS.
2) MODEL SCALE: 1 mm MODEL = 26.4 mm PROTOTYPE.
Rossdale WTP
HYDRAULIC MODELLING OF STORAGE TANKS
IN WATER DISTRIBUTION SYSTEMS
Rossdale Model - CR12
Plan View
KIH-001
REV. NO. 1
Dec-06-02

FIGURE 3-14

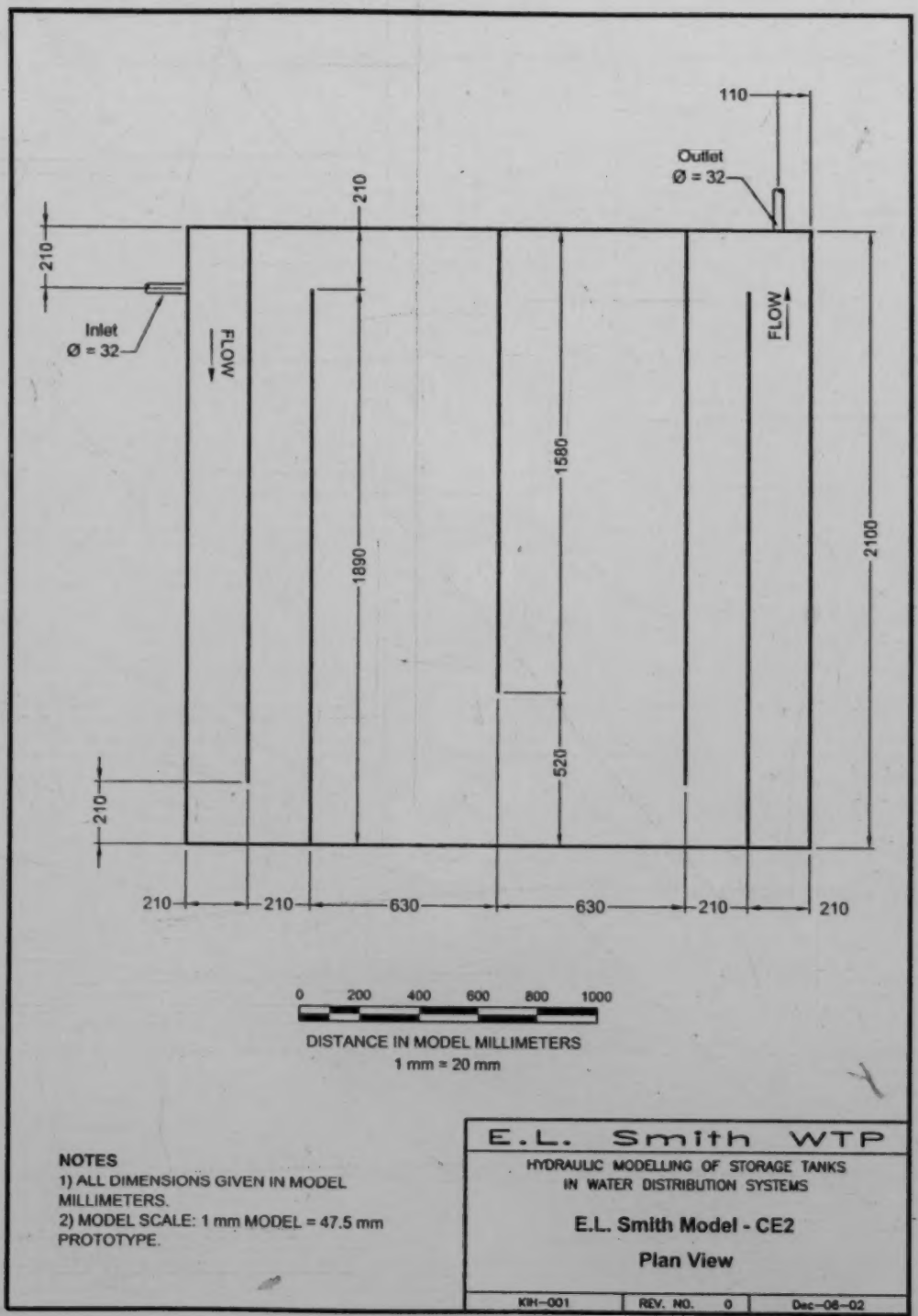
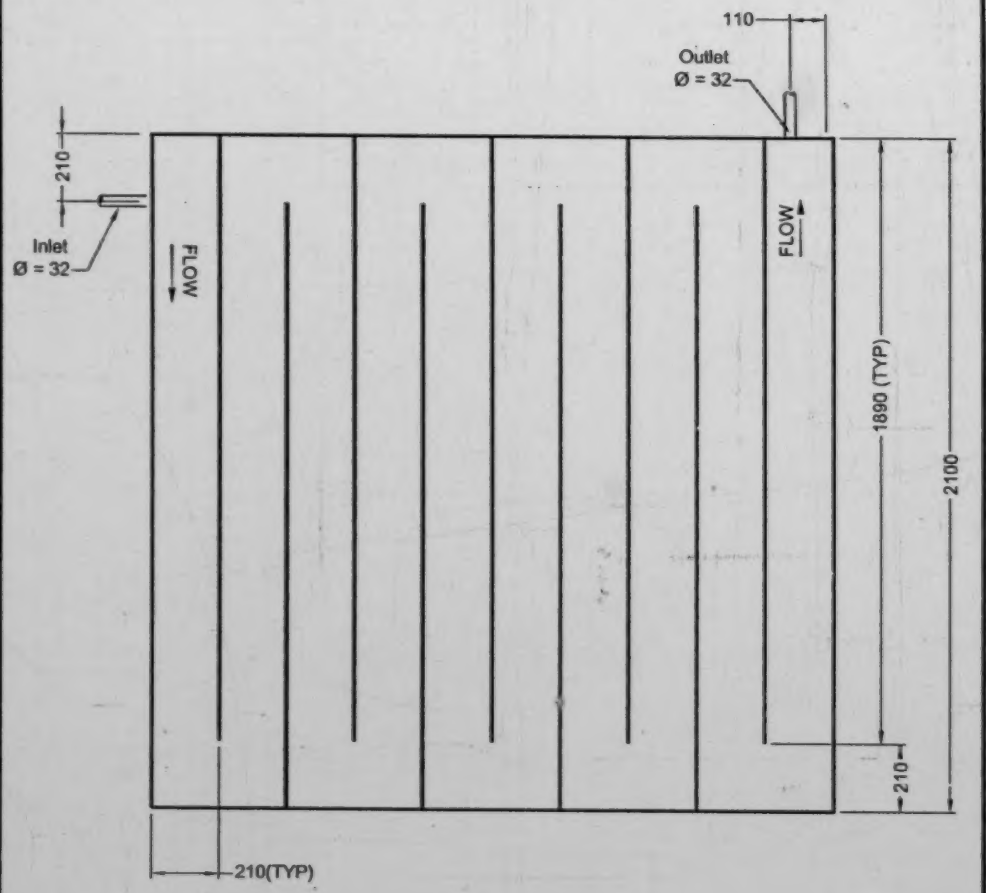
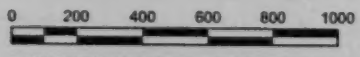

110
Outlet
Ø = 32
210
210
Inlet
Ø = 32
FLOW
FLOW
1580
1890
2100
520
210
210
210
630
630
210
210
0
200
400
600
800
1000
DISTANCE IN MODEL MILLIMETERS
1 mm = 20 mm
NOTES
1) ALL DIMENSIONS GIVEN IN MODEL MILLIMETERS.
2) MODEL SCALE: 1 mm MODEL = 47.5 mm PROTOTYPE.
E.L. Smith WTP
HYDRAULIC MODELLING OF STORAGE TANKS IN WATER DISTRIBUTION SYSTEMS
E.L. Smith Model - CE2
Plan View
KIH-001
REV. NO. 0
Dec-06-02

FIGURE 3-15





DISTANCE IN MODEL MILLIMETERS
1 mm = 20 mm

NOTES
1) ALL DIMENSIONS GIVEN IN MODEL MILLIMETERS.
2) MODEL SCALE: 1 mm MODEL = 47.5 mm PROTOTYPE.

E.L. Smith WTP

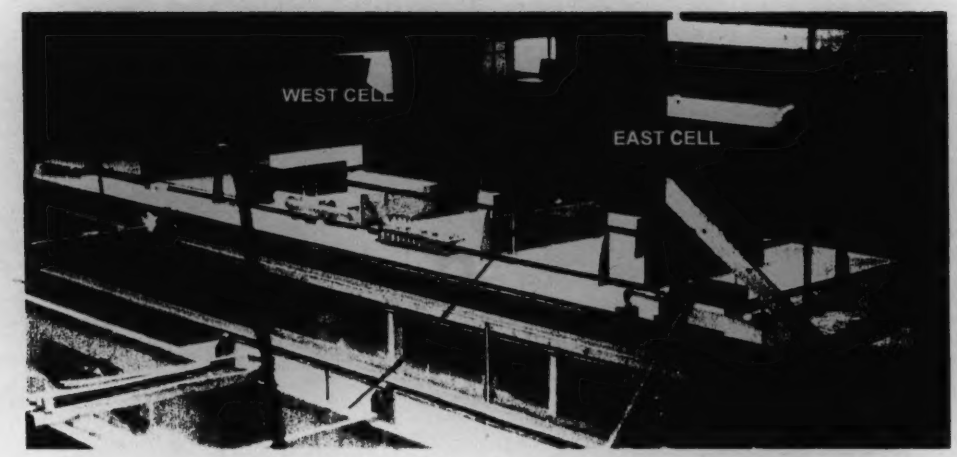
HYDRAULIC MODELLING OF STORAGE TANKS IN WATER DISTRIBUTION SYSTEMS

E.L. Smith Model - CE3

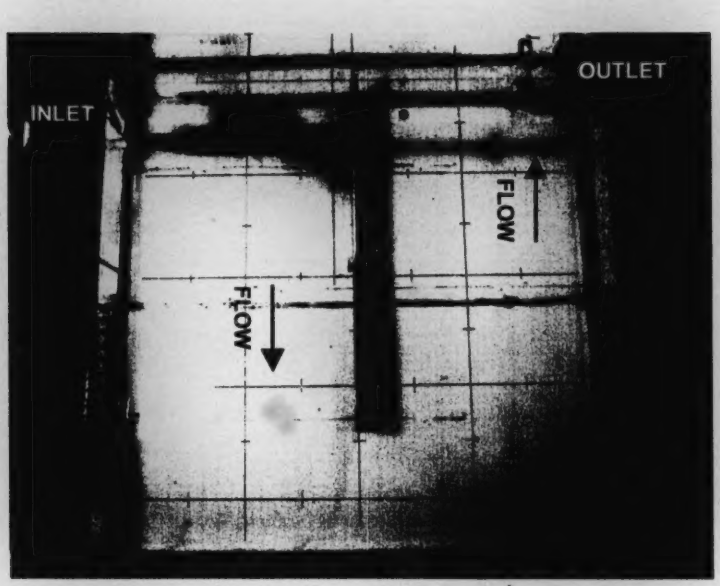
Plan View

KIH-001	REV. NO. 0	Dec-06-02

FIGURE 3-16



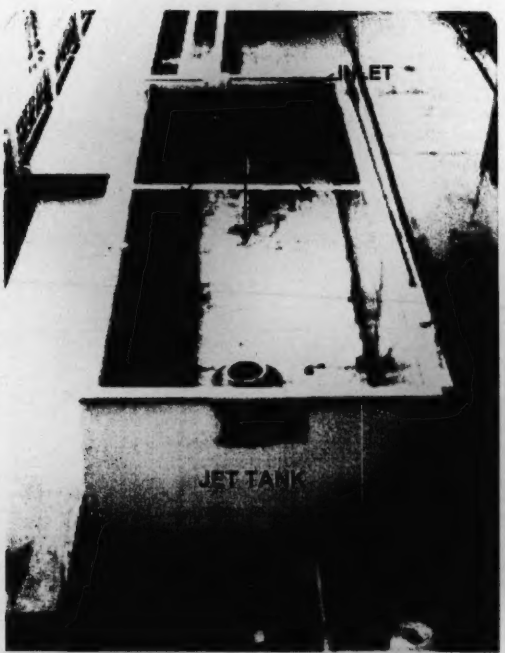
1) General view of Rossdale model.



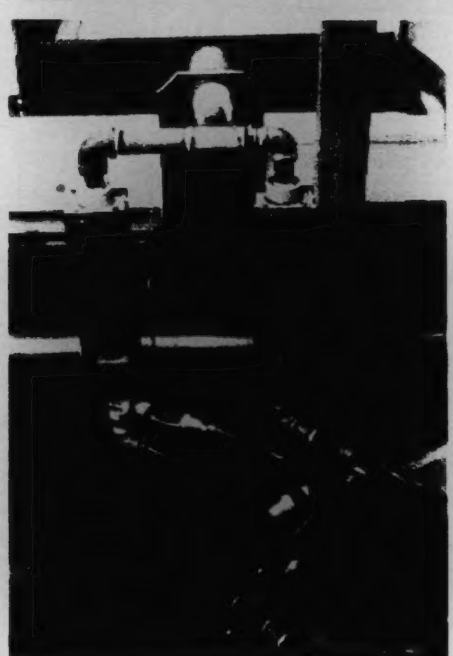
2) View of the E.L. Smith Model from above.

HYDRAULIC MODELLING
OF STORAGE TANKS IN WATER
DISTRIBUTION SYSTEMS
Model Layout

PHOTO PLATE 3-1



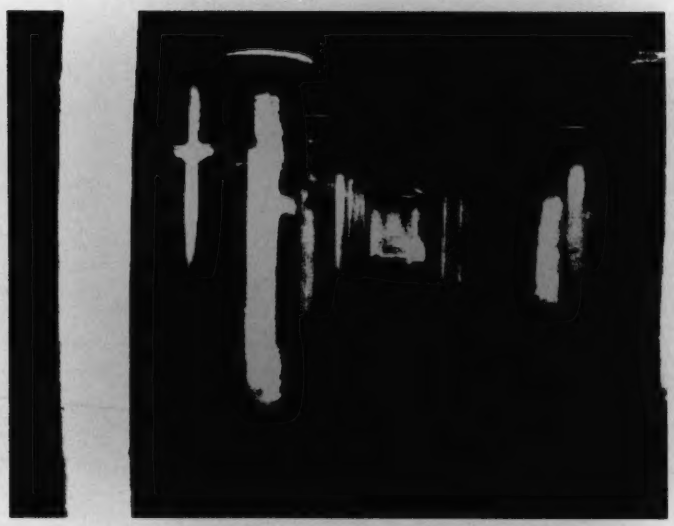
1) View of the Jet Tank used to supply the models with a mixture of water and tracer chemical.



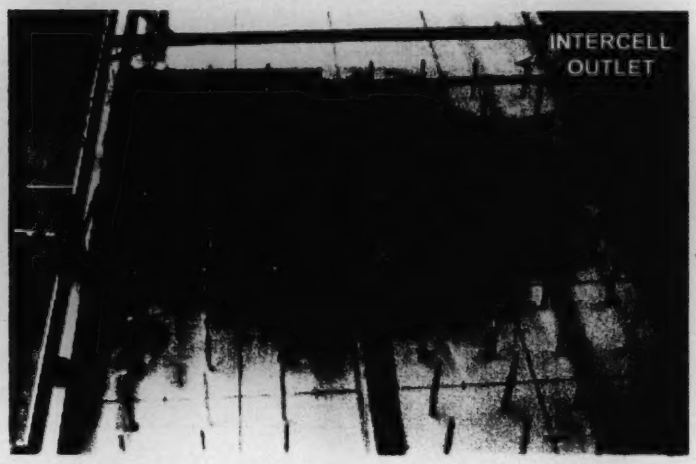
2) View of the Model 1114 Brooks full-view flowmeters used to measure discharge at the feeding line(s) in both models.

HYDRAULIC MODELLING OF STORAGE TANKS IN WATER DISTRIBUTION SYSTEMS
Influent Controls

PHOTO PLATE 3-2



1) View of the support columns from inside the storage reservoir at the Rossdale WTP *(photo by Peter Baker).*



2) View of the east cell of the Rossdale Model configuration CR2. Note that 20 mm sticks have been added to represent the prototype support columns.

Modelling of Support Columns

PHOTO PLATE 3-3

4.0 Experimental Results, Analysis and Discussion

4.1 Data Processing

For the duration of each tracer test, the time dependent concentration levels at key points within the storage tank were measured. The time, from the initial introduction of the tracer chemical at the inlet to the time of sample collection, was recorded along side each corresponding concentration reading. In the experiments, which used the Turner 10 Analog fluorometer to measure tracer concentration, the sensitivity range for the sample was noted as the 'level'. For all concentration readings determined with the Turner 10-AU fluorometer, the sensitivity range was determined automatically, and therefore the level is assumed to be equal to unity. The background concentration for the reservoir system, C_{back} and the initial concentration of the tracer solution, C_o were also recorded. For convenient reference, all the experimental data have been included in Appendix A.

The value of the dimensionless concentration ratio, C/C_o was calculated for each time dependent concentration reading and included with the data. The C/C_o value was determined using the following equation:

$$C/C_o = \frac{\left[\left(\frac{C}{level_C}\right) - \left(\frac{C_{back}}{level_{back}}\right)\right]}{C_o} \qquad (4\text{-}1)$$

where $level_C$ = the sensitivity range for the time dependent concentration

$level_{back}$ = the sensitivity range for the background concentration

For the above calculation, the background concentration and the initial tracer concentration were assumed to be steady state for the duration of the tracer test. For each experiment, the relationship between the dimensionless C/C_o ratio and

the time in minutes or F-curve was plotted. The plots are included as Figure B-1 through to Figure B-33, which are located in Appendix B. Each chart contains the F-curves for all tracer tests that have equivalent configurations, water depth and discharge. The data points have been connected with short linear segments to form a curve. The general shape of each tracer curve was examined to ensure that there are fairly smooth transitions in the tracer concentration, which helps to verify that there has been minimal interference such as changes in flow rate, or tracer feed for the duration of the test (Teefy 1996). A horizontal line was placed on each chart marking the point where C/C_o equals 0.10. The point where a curve crosses the horizontal line marks the time when 10% of the tracer has reached the sample collection point. In other words, the crossing point marks the T_{10} for the sample location that is represented by the curve. This graphical method of determining T_{10} is recommended by the USEPA in the *Guidance Manual* (AWWA 1990).

The results of each model tracer test have been summarised in Table 4-1, Table 4-2, and Table 4-3. The tables include the rate of inflow, the volume of water in the reservoir, the theoretical detention time (T_d), the effective detention time (T_{10}), and the baffle parameter (T_{10}/T_d). The volume that is occupied by the interior baffle walls has been subtracted in the calculation of water volume. The volume occupied by other objects within the tank, such as the inlet pipes, diffusers, and outlet pipes has not been subtracted because of their insignificant size in relation to the total volume of the tank. The theoretical detention time, T_d was calculated for each test using equation 2-5. As stated above, the T_{10} value was determined from the F-curve. In the exceptional cases where the concentration dropped back below the T_{10} value after the T_{10} had been reached (experiments: R15, R17, R21 and R23), the first occurrence of the T_{10} is the time that is displayed in the tables. The layout of each configuration and the details of each experiment have been described previously in chapter 3.

The results of each test conducted in the model of the Rossdale reservoir system have been summarised in Table 4-1. The values in the table identify measurements taken at the outlet, therefore represent the entire system, including both cells. The concentrations that were collected at the intercell outlet represent the hydraulic characteristics of the east cell of the Rossdale model and have been included in Table 4-2. For most of the experiments, only one intercell outlet was in operation. However, configurations CR10 and CR11 employ two intercell outlets. For the purpose of clarity, the intercell outlets for all the Rossdale tests have been labelled in Table 4-2 as either the South Intercell or the North Intercell, according to the location of the passage. The results for the E.L. Smith model are displayed in Table 4-3 and represent values determined at the outlet of the reservoir.

Flow characteristics such as short-circuiting, mixing, and stagnant flow areas have been interpreted from visual observations using a red dye tracer. Results from this type of qualitative assessment are included as comments when pertinent to a discussion regarding the tank performance.

4.2 Estimate of Uncertainty

It is important to assess the precision of quantities applied in an experimental examination. For this reason, an overview of the estimated errors involved in the measured and derived quantities of this study has been included in this section. The uncertainty interval for each quantity has been determined to represent a worse case scenario. The error calculations were completed using the methods of Topping (1957).

The flow into the reservoir system was measured using two Model 1114 Brooks Full-View Flowmeters, which have a manufacturer-specified accuracy of ±2% of

the flow rate. Due to small fluctuations in the discharge readings, the maximum error for the discharge is estimated to be slightly higher at ±4%. The precision of the water depth measurement was ±1 mm, but the error in depth is likely larger at ±3 mm or ±4% of the smallest depth. The tank dimensions are estimated to be accurate to within 20 mm and therefore ±1% of the tank width. The maximum error in the volume is computed as ±4%. Applying the maximum error in the volume and in the flow rate, the error in the theoretical detention time, T_d could reach a maximum value of ±6%.

The initial entry of the tracer into the system is recorded as occurring at time zero. Some time was required to adjust the discharge at the inlet to the system, which may have introduced some error in time. The maximum error corresponding to the start time is estimated as 7 seconds. The recorded sample time may also include errors. Withdrawal of the sample is not instantaneous and is dependent on the experimenter. The time recorded represents the time that sample withdrawal with the syringe was initialised. An error of 3 seconds is assumed as the maximum error in sample withdrawal time. There may also be an error introduced when interpolating the T_{10} value from the F-curve. For that reason, the maximum error in the T_{10} value is estimated to be ±15%. The maximum error in the T_{10}/T_d value is therefore ±16%.

The maximum error for each concentration measurement is estimated as ±20%. This error is the result of measurement accuracy, and the many factors affecting fluorescence concentration. The fluorometer manufacturer's error is ±1% of the full scale, but fluorescence concentrations are also be affected by sample temperature, photochemical decay, pH, background fluorescence and fluorescent quenching (Section 3.2). Measurement techniques may be applied to minimize these effects. As discussed in Section 3.3, various precautions were taken to reduce the errors in the concentration readings while conducting the experiments

in the model. However, some level of uncertainty is still introduced due to these factors. There was a background sample taken prior to each test. The maximum error in the accuracy of the background concentration (C_{back}) at any instant of time could reach as high as 100% of the largest C_{back}. However, this error value is very small in comparison to the tracer concentration readings surrounding the T_{10} value, which was used for analysis in this study. Although the jet tank has been designed to enable good mixing, the tracer concentration at the inlet is not perfectly homogeneous initially nor for the duration of the test. The maximum error for the initial concentration, C_o is approximated at ±15 %. By applying the above estimates of uncertainty for the concentration values, the maximum error for the C/C_o ratio was computed as ±25 %.

4.3 Model Confirmation Analysis

Model confirmation was established by comparing the results of the tracer tests performed on the scale models and the results of tests, which were conducted by Liem et al (1997) on the actual full-size tanks. Comparison with the results of the full-scale system under assessment is considered to be the best means of determining the reliability of physical models (Ackers 1987). In the present study, a comparison has been made between the T_{10}/T_d ratios and the F-curves determined from the prototype tests and the model tests. The results of this comparison are summarised in Table 4-4. The F-curves for the associated model and prototype tracer tests have been included as Figures 4-1 through 4-6. These comparisons are made to determine if the model possesses equivalent hydraulic characteristics to the prototype. All values within this section will be expressed in prototype units.

Liem et al (1997) conducted two tracer tests on the full-scale Rossdale system for two different discharge and depth combinations. The first test was performed at a prototype discharge of 150 ML/d and water depth of 6.3 m, which resulted in a

T_{10}/T_d ratio of 0.40. The second test was conducted at a discharge of 130 ML/d and a depth of 5.8 m and produced a T_{10}/T_d ratio of 0.41. In this study, the third configuration of the Rossdale model was representative of the existent prototype system. Two tracer tests, R7 and R11 were conducted in the model at a flow rate of 150 ML/d and one model test; R12 was performed at 130 ML/d.

Experiment R7 was run with a water depth of 6.3 m and resulted in a T_{10}/T_d ratio of 0.35. The T_{10}/T_d ratio for the model test was 13% lower than the prototype value, which indicates that the model was experiencing a higher degree of short-circuiting than the prototype. For this model test, the water level was above the baffle wall elevation and a visualisation test showed that a portion of the water in the model was short-circuiting over the centre baffle towards the outlet. Further research of the prototype system uncovered that in reality the height of the baffle walls extended higher than what was indicated by the prototype drawings. It was concluded that for all operational water depths, the walls project above the water level. It is for this reason that the water level was lowered below the baffle wall height for a second test, R11. Although the model test was run at a depth of 4.4 m rather than the 6.3 m water depth used by Liem et al (1997), the test resulted in a T_{10}/T_d ratio of 0.37, which is within 8% of the prototype value.

In this study, the second prototype test that was conducted by Liem et al (1997) was closely mimicked by experiment R12 in the model. The full-scale test was run at a discharge of 130 ML/d and a 5.8 m water depth. The model test was conducted at a slightly lower discharge and depth. Experiment R12 was run at a discharge of 121 ML/d and the water depth was 4.6 m, so that the water level remained below the height of the baffle walls. The model test resulted in a T_{10}/T_d value of 0.40, which is a difference of only 2% from the prototype value of 0.41. In terms of the T_{10}/T_d ratio, the results indicate that the Rossdale model adequately simulates the flow patterns produced by the prototype reservoir.

Results for the east cell of the Rossdale system were also analysed for similarities between the model and the prototype. The results were taken from the same tracer tests used to examine the two-cell reservoir system, discussed above. The T_{10}/T_d values for the east cell are taken from the concentration curves measured at the intercell outlet. In the prototype tests, the T_{10}/T_d ratio was determined to be 0.72 and 0.64 for the east cell at flow rates of 150 ML/d and 130 ML/d, respectively. The model tests at the 150 ML/d discharge resulted in a T_{10}/T_d ratio of 0.47 for the test run with a 6.3 m water depth, and 0.67 for the test at a 4.4 m water depth. As expected, when the water depth in the model was above the centre baffle wall height it produced a much smaller T_{10}/T_d ratio than found in the prototype. When the water depth was lowered to 4.4 m, the ratio was within 7% of the prototype value. Model test R12, which was run to reflect the 130 ML/d prototype discharge, produced a baffle parameter of 0.60 for the east cell, which is only 6% smaller than the prototype ratio. In terms of the baffle parameter, the results for the east cell of the Rossdale system also indicate that the hydraulics in the prototype are adequately reproduced by a physical model with a scale factor of 26.4.

The F-curves of the prototype and the model of the Rossdale combined storage reservoir also correlate relatively well. The point of tracer injection and the outflow concentration measurement are in similar locations for both the model and prototype for the Rossdale system, so a direct comparison of the F-curves can be made (Falconer & Tebutt 1986). As can be seen in Figures 4-1 through 4-6, the F-curves for both the prototype and model are similar for both the entire two-cell system and those of the east cell alone.

Modifications developed during the present physical model study have been since integrated into the full-scale Rossdale reservoir system. The prototype reservoirs

were modified into a similar layout to model configuration CR12. Stantec Consulting Ltd. (2001) conducted testing on the prototype structure after the modifications were completed. Two prototype tests were performed on this configuration both at a discharge of 170 ML/d. One prototype test was conducted at an approximate water depth of 3.5 m and the other at an approximate depth of 6 m. The results are displayed in Table 4-5. Experiment R31 in configuration CR12 of the model was conducted at a discharge of 150 ML/d and a depth of 6.3 m. When compared, the T_{10}/T_d ratio for the model is within 4% of the prototype for the combined reservoir system and within 8% for the east cell of the system. The data retrieved by Stantec (2001) for this new configuration supports the findings that the model is a good representation of the prototype.

A noteworthy observation with regard to these comparisons is that the discharge used in experiment R31 is 12% smaller than the Froude scaled discharge of that applied during the prototype tracer tests by Stantec (2001). Nevertheless, the results show a very good correlation. In addition, when the model discharge is 7% lower than the Froude scale discharge, as is the case for the Rossdale model test R12 performed at 121 ML/d, the model F-curve shows a better correlation with its prototype curve. As mentioned in the literature review, Hart and Gupta (1978), Hart (1979), and Hart and Vogiatzis (1982) found that a smaller discharge than implied by the Froude criteria might be a better representation of the hydraulic attributes of this type of system. This raises the question whether in fact there is only a weak Froude relationship between the model and prototype of water treatment storage tanks. It opens the possibility that precise Froude similarity may not be necessary and that it is geometric and kinematic similarity that dominate. There is generally only a slight gradient of the water depth at the outlet of a storage tank, so the idea that the effects of gravity might be minimal seems reasonable. This concept was not further investigated within the scope of this study, but should be further pursued in future studies. For the time being, it

would be prudent to design physical models with sufficiently large Reynolds numbers to minimise viscous effects and to compare model results to prototype results.

Additional information was noted during the model confirmation process. In the early stages of testing, an experiment was performed to determine whether the addition of scaled-down pillars in the model was necessary to reproduce the prototype flow behaviour. Circular sticks were added to the Rossdale model to resemble the pillars found in the prototype and this configuration was termed CR2. When compared to the results of configuration CR1, it is apparent that the pillars do not significantly affect the T_{10}/T_d. However, when the flow conditions were observed visually with a coloured dye, it was shown that the pillars marginally improve the longitudinal mixing of the dye within the tank. Even with this slight improvement to the longitudinal mixing, the results suggest that the pillars are not required in the hydraulic model to properly represent the flow characteristics of the full-scale system.

The results of the E.L. Smith model also support the conclusion that an adequate reproduction of the flow characteristics within a chlorine contact tank can be reached with the use of physical models based on Froude criterion. Liem et al (1997) performed two tracer tests in the E.L. Smith reservoir. One of the prototype tests was run at a discharge rate of 230 ML/d and a water depth of 3.9 m. The T_{10}/T_d ratio for this prototype test was determined as 0.19. The other prototype test was conducted at 180 ML/d with a water depth of 4.1 m and resulted in a T_{10}/T_d ratio of 0.27.

The E.L. Smith model was built using a scale factor of 47.5. Five tracer tests, E1 through E5 were performed in the initial model configuration. Experiment E1 was performed at a flow rate of 250 ML/D and water depth of 4.2 m, which resulted in

a T_{10}/T_d ratio of 0.17. Experiment E2 and E5 were both conducted at a discharge of 230 ML/d and water depth of 3.9 m. The T_{10}/T_d ratio for these two tests was 0.20 and 0.18, respectively. Referring back to Table 4-4, it is apparent that there is good correlation between the T_{10}/T_d value of the prototype and the measured model ratios for the E. L. Smith reservoir near this flow rate. In the order of test number, the T_{10}/T_d ratio only diverges from the prototype value by 9%, 7%, and 3%.

Two tracer tests, E3 and E4 were performed on the model at a discharge equivalent to 181 ML/d and a water depth of 4.1 m. Experiment E3 and E4 resulted in a T_{10}/T_d ratio of 0.17 and 0.20, respectively. These values translate into differences of 36% and 25% from the prototype ratio. The significant difference between the T_{10}/T_d values for the prototype and the model were a source of concern, hence further investigation was conducted. It was observed that the T_{10}/T_d ratios for the model at 181 ML/d are very similar to the values determined for both the model and prototype tests at the 230 ML/d discharge. The baffle parameters measured by Liem et al (1997) showed a 42% difference for the two prototype tests, even though the discharges varied by only 50 ML/d or 22%. For this relatively small difference in the discharge rates, the T_{10}/T_d value is not expected to differ by such a significant amount. It has been assumed that the T_{10}/T_d value was incorrectly measured for the full-scale reservoir at the 180 ML/d discharge. This assumption was supported by the results of the other two baffle configurations for the E.L. Smith model, which did not show a significant difference in the T_{10}/T_d values between these two discharges. It has been determined that the model results for the baffle parameter are a good estimate of the full-scale system results at the E.L. Smith WTP.

The model and prototype F-curves for the E.L. Smith reservoir exhibit slight discrepancies when compared. The point of tracer injection and the outflow

concentration measurement locations are marginally different for the E.L. Smith model. The sample point at the model inlet is slightly downstream of the sample point in the prototype and the model outlet is slightly upstream of that for the prototype. For this reason, the prototype tracer has a slightly longer travel distance and the model is expected to exhibit a slight upstream shift of the F-curve. The experimental results confirm this. The time interval for the initial indication of tracer in the effluent, t_i is smaller in the model than in the prototype.

4.4 Analysis of the Effects of Design Parameters on Tank Performance

4.4.1 Internal Baffle Configuration

Baffle walls are added to storage basins in order to extend the travel distance of the flow circulating through the tank, thereby prolonging the fluid's residence time. A well-designed layout of baffle walls in a distribution tank provides a path for the fluid to follow, while still allowing it to mix laterally as it travels through the system. The objective of the system is to provide good mixing and adequate contact time with the chemicals used for disinfection, while minimising flow short-circuiting and stagnant flow areas.

As mentioned in chapter two, the ratio of the length of travel to the channel width created by the addition of baffle walls is commonly the focus of studies regarding storage tank design. In this study, the E.L. Smith model testing offers the clearest example of the effects of baffle wall addition. For all three configurations, the inlet and outlet were similar and the design modifications consisted of a very systematic addition of baffle walls. Table 4-6 summarises the L: W ratio and the resulting T_{10}/T_d ratio for each of the E.L. Smith tests including the prototype tests. The baffle wall layout in the east cell of the Rossdale reservoir was also simple enough to compare in this manner for a number of the configurations and have therefore been added to the table. The results indicate that the T_{10}/T_d ratio increases as the L:W ratio is increased. As shown in Figure 4-7, the T_{10}/T_d ratio does not increase significantly beyond a L:W ratio of 30:1. As discussed in

chapter two, Bishop et al (1990, 1993) found that that there was limited improvement in many of the performance indices when the L:W ratio reaches approximately 20:1. Both of these findings indicate that an improvement in the hydraulic efficiency occurs as the L:W ratio increases, but only up to an optimal value.

From visual observations using a coloured dye, it is apparent that the flow characteristics improve with the addition of baffle walls. This is depicted in Photo Plate 4-1, which is a photographic comparison of the dye pattern during visualisation tests in each of the three E.L. Smith model configurations. As shown in the photos, the amount of stagnant areas or dead space in the tank and the amount of flow short-circuiting diminish as the baffle walls are added to the tank. It can be seen that the reservoir approaches the ideal plug flow condition as the L:W ratio increases. This is also illustrated in Figures 4-8 and 4-9, which show the progression of the F-curve as baffle walls are added to the E.L. Smith model. The F-curves for the ideal CSTR and ideal PFR flow conditions have been added to the charts to help demonstrate this fact.

The relationship between the L:W ratio and the baffle parameter was more difficult to assess for the more complex baffle arrangements. For example, many of the internal baffle configurations for the Rossdale model can not be described as a fixed number of equally spaced baffle walls and do not exhibit equal channel widths throughout the system. To provide a general relationship for the more complex baffle wall layouts, data from both model tests as well as the full-scale tracer tests were analysed. It was found that if one estimates the travel distance water must flow to get from the inlet to the outlet of the reservoir and divide it by the water depth within the reservoir (L:D), this parameter correlates well with the T_{10}/T_d value. This non-dimensional relationship is illustrated in Figure 4-10. The values used for this comparison are summarised in Table 4-7 and 4-8. The tests conducted with two inlets (R8 to R10) or two intercell outlets (R26 to R29) in

operation were not included in the comparison. The L:D ratio and the T_{10}/T_d value for both reservoirs relate along a linear path with the following equation:

$$T_{10}/T_d = 0.0043(L:D) \qquad (4\text{-}2)$$

where T_{10}/T_d = *baffle parameter*
L:D = length of travel from inlet to outlet divided by water depth

It is recommended in the *Guidance Manual* (AWWA 1989) that the T_{10}/T_d of a contact basin be estimated by referencing typical baffling designs, whenever conducting tracer studies is not a practical alternative. The results of this study have been compared with the method of classification given by the *Guidance Manual* and summarised in Table 4-9. The results show that the T_{10}/T_d values are overestimated by this method, and that the actual conditions tend to be worse for the poor to average baffling conditions. The T_{10}/T_d ratio for configurations within the category of the 'superior' baffling condition fluctuated both above and below the estimated value. However, on average the experimental values compared relatively well with the T_{10}/T_d given for that category. The E.L. Smith and Rossdale reservoirs did differ slightly from the descriptions given in the *Guidance Manual* classification. For instance, many of the internal tank configurations that were tested had inlet installations such as flow diffusers or pipe elbows, as opposed to the inlet or outlet baffles that were described in the *Guidance Manual*.

4.4.2 Inlet Design

For both the Rossdale and E.L. Smith storage basins, water enters the tank through the inlet as a circular turbulent jet. Then once the jet dies out and the Reynolds number has decreased below its critical value, the flow approaches the exit due to a water surface gradient, which is gravity controlled. It is fairly common practice for researchers to look to the inlet and/or outlet design of a

contact basin when searching to extend the residence time. In this study, an effort was made to design a more effective inlet as a means of both spreading the flow laterally and decreasing the momentum of flow entering the tank. The objective was to approach a plug flow condition through the tank and increase the time the water spends within the tank. A fairly basic investigation of a few different inlet designs was conducted. Modifications to the existing tank inlets included the installation of a short baffle wall in front of the inlet, the addition of flow diffusers, and the addition of a pipe elbow at the inlet. An investigation of these inlet designs was completed using the Rossdale model.

There are two types of inlet designs installed in the original configuration of the Rossdale reservoir. At the inlet to the system there is a pipe elbow directed downward into a trench. In prototype units, the trench is 3300 mm deep, 4488 mm wide and 6768 mm long. At the intercell outlet, there is a 19536 mm long baffle wall set 10560 mm downstream of the jet entering the west cell. The effectiveness of these two inlet designs was investigated in the model by comparing the results of tests in the original configuration, CR3 with those of configuration CR1. Diagrams of the configurations can be referenced in Figure 3-2 and Figure 3-6, respectively. Both configurations have the same internal geometry, but the additions to the inlet and intercell outlet are absent in CR1. The influent in CR1 travels into the east cell directly from a 50 mm (model units) diameter influent pipe. The intercell outlet, which is a 1500 mm butterfly valve, was represented in the model by a 57 mm circular passage between the two cells. The flow enters both cells in CR1 in the form of a circular turbulent jet. When comparing the inlets of configurations CR1 and CR3, the entrenched pipe elbow of CR3 performed better due to its ability to provide a reasonably effective method of dissipating the momentum of the influent. The T_{10}/T_d value for the east cell increased from 0.15 to approximately 0.37 with the addition of the pipe elbow. The installation of a baffle wall in the west cell, just downstream of the intercell

outlet, did not appear to improve the tank performance. From visual observations, it was evident that flow moved easily around both sides of the baffle wall and towards the outlet without any significant effect to the tank performance.

The use of flow diffuser pipes was also examined during this study. Each flow diffuser was comprised of a segment of pipe with a number of circular holes cut along its length. The pipe was then installed perpendicular to the influent jet. This divided the influent jet into a number of smaller jets. The total open area in the diffuser that allows for fluid passage is larger than that of the influent pipe cross-sectional area. Conceptually, the diffuser should both spread the influent across a wider area to improve mixing and decrease the flow momentum at the entrance to the basin. The geometry of the flow diffusers that were tested in this study can be referenced in Figure 3-9 and Figure 3-12.

The first flow diffuser that was tested was installed in configuration CR5. A diffuser was installed at both the inlet and the intercell outlet, and both consisted of a single row of 15 mm diameter holes, which added up to a total open area of 5300 mm^2. The effect of the diffuser installation can be observed by comparing the results of tests in CR4 and CR5. Configuration CR4 has the same internal geometry as CR5, but without the flow diffusers. The visualisation tests indicated a small improvement in the mixing at the entrance to each cell. The addition of the flow diffusers also marginally increased the T_{10}/T_d value from 0.50 to 0.54 for the system and from 0.46 to 0.48 for the east cell.

The same diffuser design was also used at the inlet to configuration CR6. However, a new diffuser design was tested at the intercell outlet. The intercell outlet diffuser in CR6 had two rows of 15 mm diameter openings, and a metal plate within the diffuser pipe with 22 mm openings arranged in the pattern shown in Figure 3-9. It is difficult to compare the results of the new diffuser design in the

west cell, because the T_{10} for the west cell alone is not simple to determine. In order to establish this value, it would have to be assumed that the tracer input to the west cell is essentially a step input. However, the actual tracer input curve is unknown and any loss of tracer in the east cell will affect the results of the west cell. Visually, the new design appeared to induce good mixing both vertically and horizontally. In configuration CR7, this type of diffuser design with an internal perforated plate was applied again. The arrangement of the openings in the metal plate of both the inlet and the intercell outlet diffusers can be referenced in Figure 3-9. Visualisation tests with a coloured dye indicated that flow exiting both diffusers mix well in both the vertical and the horizontal directions.

A more intricate exit pattern was used for the flow diffusers in configuration CR8. The diffuser was designed using smaller openings at the centre of the diffuser, where the flow from the inlet pipe is concentrated, and increasingly larger holes towards the outside edges. The total open area of the exit holes was 7720 mm^2. The pattern of holes was designed with the intention of improving lateral mixing and keeping even flow velocities along the diffuser pipe. The T_{10}/T_d value for this configuration was compared to CR7, which shares a similar internal tank geometry. The varying exit hole sizes and pattern of CR8 did not significantly increase the retention time above that which resulted from the diffuser design in CR7. In fact, the T_{10}/T_d ratio remained at 0.74 at the 29.1 L/min discharge for both configurations.

Configuration CR9 applied a diffuser at the inlet with a simple four hole pattern. The primary difference in this design was that the openings were directed towards the outside wall of the tank rather than towards the tank's interior, as in previous configurations. It was observed through visualisation testing, that when the jets from the diffuser impact the wall, the coloured dye spreads well in the vertical direction. However, the momentum of flow from the influent pipe, which lays

along the dividing wall between the two cells, causes the leading edge of the dye to concentrate along the north wall of the cell.

The inlet diffuser of both configuration CR10 and CR11 had the same exit hole pattern as the inlet in CR9. At the intercell outlet of both configurations, a 3 hole diffuser pipe was installed. Again, the openings of both diffusers faced the wall of the tank. The diameter of the holes in the diffusers in CR10 and CR11 differed by 10 mm. The diameter of all the diffuser openings in CR11 were larger than those in CR10, and consequently there was an increased open area for the fluid to pass. The openings were enlarged in an attempt to reduce the velocity of the flow entering the reservoir. The increased open area allowed for a small improvement in the mixing, but did not make a significant difference in the T_{10}/T_d value.

In general, the addition of a flow diffuser at the inlet to the tank improves the mixing characteristics in both the vertical and lateral directions. The tracer tests conducted in this study were not sufficient enough to show whether the diffuser pipe has a significant impact on the T_{10}/T_d value. However, when the openings of the diffuser were directed towards the wall of the tank rather than towards the interior of the tank, there appeared to have been a significant decrease in the momentum of flow at the outset.

Another type of inlet design was installed in configuration CR12. It was a 45 degree pipe elbow connected to the influent pipe and aimed towards the back wall of the reservoir. With this design installed, the flow enters the cell through the pipe elbow and travels towards the back wall of the tank as a circular turbulent jet. It then collides with the back wall and much of the jet's momentum is lost. Visualisation tests showed that the dye mixes well in both the vertical and lateral directions as it is deflected off the back wall and begins travelling through the maze of baffle walls towards the intercell outlet. Although there were no tests

conducted in this study that allow for an accurate comparison of the T_{10}/T_d value with and without the pipe elbow installed, this was a preferred design because of its simplicity and its performance with regards to mixing.

4.5 Analysis of the Effects of Operational Parameters on Tank Performance

4.5.1 Water Level

The operating conditions for several of the tank configurations in the present study varied from test to test, so as a secondary consideration the T_{10}/T_d ratio resulting from these tracer tests was compared to observe whether the operating conditions have an affect on tank performance. In the first phase of testing in the Rossdale model, a number of the tracer tests that were performed in a particular configuration had all parameters held equal except for the water level. The resulting T_{10}/T_d ratio of each of these tests was compared to examine whether the variations in the water depth have an effect on the baffle parameter. In CR1, three different water levels were tested. The depth of water ranged from 273 mm down to 220 mm, which translates to a depth decrease of approximately 19%. This set of tests showed no significant change in the T_{10}/T_d ratio. The results of testing in the third configuration of the Rossdale model also indicate that changes in the water level do not produce a distinct change in the T_{10}/T_d ratio. The water depths tested in CR3 varied from 167 mm to 239 mm at the lower of the two discharges tested, and from 239 mm to 265 mm at the higher discharge. For as much as a 30% change in the water level, no significant difference in the tank performance was observed. However, when the water level was raised above the height of the baffle walls, there was fluid short-circuiting over the walls towards the outlet, and in turn there was a notable decreased in the T_{10}/T_d ratio. For that reason, the water level should be kept below the height of the baffle walls in order to make optimal use of the internal wall design.

4.5.2 Discharge

The Rossdale model results were also examined for potential patterns, which may be attributed to varying the discharge through the tank. Results that were chosen for comparison came from tests that were conducted in one configuration, had equal water depths, and consequently an equal water volume. The results of six different configurations of the Rossdale model were used for this purpose. A summary of the resulting T_{10} and T_{10}/T_d values of these tests is presented in Table 4-11. As expected, in all cases the T_{10} decreased as the discharge increased. However, this did not necessarily translate into a decrease in the T_{10}/T_d value for all the configurations. In fact, tests in configurations CR6, CR7 and CR9 showed a significant increase in the T_{10}/T_d value with an increasing discharge. Tests in configuration CR1 and CR11 showed only a marginal increase, and tests in CR12 showed a decrease in the T_{10}/T_d value. The largest range of flow rates was tested in configuration CR6. At the largest variance between two discharges, which was a difference of 38.8 L/min, the T_{10}/T_d value differed by 0.23. Therefore, for an 80% drop in the discharge, there was a 29% drop in the T_{10}/T_d value. However, this substantial change in the T_{10}/T_d value associated with the discharge was not observed for all configurations. Further research is required for a better understanding of the effects of discharge on the tank performance.

Table 4-1. Summary of Experimental Results for the Rossdale Model

Configuration (1)	Experiment (2)	Qm (L/min) (3)	Volume (L) (4)	T_d (min) (5)	T_{10} (min) (6)	T_{10}/T_d (7)
Phase 1: Model Confirmation						
CR1	R1	29.1	5399	186	46	0.25
	R2	29.1	5399	186	46	0.25
	R3	14.5	5399	371	84	0.23
	R4	29.1	4727	162	38	0.23
	R5	29.1	4351	150	38	0.25
CR2	R6	29.1	4723	162	37	0.23
CR3	R7	29.1	4695	161	56	0.35
	R8*	58.2	4695	81	10	0.12
	R9*	58.2	5206	89	6	0.07
	R10*	58.2	4695	81	10	0.12
	R11	29.1	3281	113	42	0.37
	R12	23.5	3418	146	58	0.40
Phase 2: Design Modifications						
CR4	R13	29.1	4695	161	80	0.50
CR5	R14	29.1	4695	161	87	0.54
CR6	R15	29.1	4613	159	105	0.66
	R16	9.7	4613	476	265	0.56
	R17	48.5	4613	95	75	0.79
	R18	38.8	4613	119	97	0.82
CR7	R19	29.1	4613	159	118	0.74
	R20	58.2	4613	79	63	0.79
	R21	29.1	4613	159	118	0.74
	R22	38.8	4613	119	95	0.80
CR8	R23	29.1	4613	159	118	0.74
CR9	R24	41.7	Test of East Cell Exclusively			
	R25	58.2				
CR10	R26	58.2	4698	81	49	0.61
CR11	R27	58.2	4698	81	52	0.64
	R28	58.2	4698	81	47	0.58
	R29	29.1	4698	161	93	0.57
CR12	R30	58.2	4676	80	49	0.61
	R31	29.1	4676	161	113	0.70

* Two inlets operating.

Table 4-2. Summary of Results for the East Cell of the Rossdale Model

Configuration	Experiment	Volume (L)	T_d (min)	T_{10} (min) South Intercell	T_{10}/T_d South Intercell	T_{10} (min) North Intercell	T_{10}/T_d North Intercell
(1)	(2)	(4)	(5)	(6)	(7)	(8)	(9)
Phase 1: Model Confirmation							
CR1	R1	2696	93	n/a	n/a	12	0.13
	R2	2696	93	n/a	n/a	15	0.16
	R3	2696	185	n/a	n/a	19	0.10
	R4	2361	81	n/a	n/a	12	0.15
	R5	2173	75	n/a	n/a	12	0.16
CR2	R6	2361	81	n/a	n/a	13	0.16
CR3	R7	2342	81	n/a	n/a	30	0.37
	R8	2342	80	n/a	n/a	41	0.51
	R9	2597	89	n/a	n/a	31	0.35
	R10	2342	80	n/a	n/a	24	0.30
	R11	1637	56	n/a	n/a	36	0.64
	R12	1705	73	n/a	n/a	42	0.58
Phase 2: Design Modifications							
CR4	R13	2342	81	37	0.46	n/a	n/a
CR5	R14	2342	81	39	0.48	n/a	n/a
CR6	R15	2324	80	44	0.55	n/a	n/a
	R16	2324	240	86	0.36	n/a	n/a
	R17	2324	48	36	0.75	n/a	n/a
	R18	2324	60	39	0.65	n/a	n/a
CR7	R19	2324	80	51	0.64	n/a	n/a
	R20	2324	40	27	0.68	n/a	n/a
	R21	2324	80	54	0.68	n/a	n/a
	R22	2324	60	42	0.70	n/a	n/a
CR8	R23	2324	80	55	0.69	n/a	n/a
CR9	R24	2353	56	21	0.36	n/a	n/a
	R25	2353	40	17	0.42	n/a	n/a
CR10	R26	2356	40	21	0.44	18	0.44
CR11	R27	2356	40	23	0.51	21	0.51
	R28	2356	40	19	0.42	17	0.42
	R29	2356	81	40	0.44	36	0.44
CR12	R30	2341	40	n/a	n/a	19	0.47
	R31	2341	80	n/a	n/a	48	0.60

Table 4-3. Summary of Experimental Results for the E.L Smith Model

Configuration (1)	Experiment (2)	Qm (L/min) (3)	Volume (L) (4)	T_d (min) (5)	T_{10} (min) (6)	T_{10}/T_d (7)
Phase 1: Model Confirmation						
CE1	E1	11.2	389	35	6	0.17
	E2	10.3	360	35	7	0.20
	E3	8.1	378	47	8	0.17
	E4	8.1	378	47	9	0.20
	E5	10.3	360	35	6	0.18
Phase 2: Design Modifications						
CE2	E6	10.3	347	34	25	0.74
	E7	10.3	347	34	23	0.68
	E8	8.1	365	45	34	0.75
	E9	8.1	365	45	31	0.68
CE3	E10	10.3	334	32	27	0.83
	E11	10.3	334	32	29	0.89
	E12	8.1	351	44	39	0.90
	E13	8.1	351	44	39	0.90

Table 4-4. Comparison of Prototype and Model Tracer Test Results

Reservoir	Prototype			Model (equivalent prototype units)				Difference in T_{10}/T_d
	Discharge	Depth	T_{10}/T_d	Model	Discharge	Depth	T_{10}/T_d	[Proto-Model]/Proto
	(ML/D)	(m)	Prototype	Test No.	(ML/D)	(m)	Model	(percentage)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Rossdale	150	6.3	0.40	R7	150	6.3	0.35	-13%
Combined				R11	150	4.4	0.37	-8%
	130	5.8	0.41	R12	121	4.6	0.40	-2%
Rossdale	150	6.3	0.72	R7	150	6.3	0.47	-35%
East Cell				R11	150	4.4	0.67	-7%
	130	5.8	0.64	R12	121	4.6	0.60	-6%
E.L. Smith	230	3.9	0.19	E1	250	4.2	0.17	-9%
				E2	230	3.9	0.20	7%
				E5	230	3.9	0.18	-3%
	180	4.1	0.27	E3	181	4.1	0.17	-36%
				E4	181	4.1	0.20	-25%

*Prototype results adapted from *RTD Analysis as Related to the Effective Contact Time* by Liem et al, 1997

Table 4-5. Comparison of Prototype and Model Tracer Test Results - Modified Configuration

Rossdale	Prototype			Model (equivalent prototype units)				Difference in T_{10}/T_d
	Discharge	Depth	T_{10}/T_d	Model	Discharge	Depth	T_{10}/T_d	[Proto-Model]/Proto
	(ML/D)	(m)	Prototype	Test No.	(ML/D)	(m)	Model	(percentage)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
East Reservoir	170	~3,5	0.65	R31	150	6.3	0.60	-8%
	170	~6	0.65					-8%
Combined Reservoirs	170	~3,5	0.67	R31	150	6.3	0.70	4%
	170	~6	0.72					-3%

*Prototype results adapted from *Rossdale Tracer Study 2000* by Stantec Consulting Ltd., 2001

Table 4-6. Dependence of Baffle Parameter on Length to Width Ratio

Configuration (1)	Experiment (2)	Number of Baffles (3)	Travel Distance (mm) (4)	Width (mm) (5)	L/W (6)	T_{10}/T_d (7)
E.L. Smith Model Phase 1: Model Confirmation						
CE1	E1	1	5460	1050	5.2	0.17
	E2					0.20
	E3					0.17
	E4					0.20
	E5					0.18
E.L. Smith Model Phase 2: Design Modifications						
CE2	E6	5	13030	210/630	37.2	0.74
	E7					0.68
	E8					0.75
	E9					0.68
CE3	E10	9	20590	210	98.0	0.83
	E11					0.89
	E12					0.90
	E13					0.90
E.L. Smith Prototype Tests (Liem 1994)						
Prototype	-	1	259896	49833	5.2	0.27
for CE1	-					0.19
East Cell Rossdale Model Phase 2: Design Modifications						
CR4	R13	5	12550	770	16.3	0.46
CR5	R14	5	12550	770	16.3	0.48
CR6	R15	5	12550	770	16.3	0.55
	R16					0.36
	R17					0.75
	R18					0.65
CR7	R19	7	15470	590	26.2	0.64
	R20					0.68
	R21					0.68
	R22					0.70
CR8	R23	7	15470	590	26.2	0.69

Table 4-7. Dependence of Baffle Parameter on Travel Distance to Volume Ratio for Rossdale Reservoir

Configuration	Experiment	Travel Distance (mm)	Water Depth (mm)	L/D	T_{10}/T_d
(1)	(2)	(3)	(4)	(5)	(6)
Phase 1: Model Confirmation					
CR1	R1	11946	273	44	0.25
	R2		273	44	0.25
	R3		273	44	0.23
	R4		239	50	0.23
	R5		220	54	0.25
CR2	R6	11946	239	50	0.23
CR3	R7	13528	239	57	0.35
	R8*		239	57	0.12
	R9*		265	51	0.07
	R10*		239	57	0.12
	R11		167	81	0.37
	R12		174	78	0.40
Design Modifications					
CR4	R13	23132	239	97	0.50
CR5	R14	23132	239	97	0.54
CR6	R15	36433	239	152	0.66
	R16		239	152	0.56
	R17		239	152	0.79
	R18		239	152	0.82
CR7	R19	39353	239	165	0.74
	R20		239	165	0.79
	R21		239	165	0.74
	R22		239	165	0.80
CR8	R23	39353	239	165	0.74
CR9	R24	8560	239	36	0.36
	R25		239	36	0.42
CR10	R26	11508	239	48	0.61
CR11	R27	11508	239	48	0.64
	R28		239	48	0.58
	R29		239	48	0.57
CR12	R30	28161	239	118	0.61
	R31		239	118	0.70
Field Tests on Prototype by Liem 1997					
Prototype	-	354829	6300	56	0.40
for CR3	-		5800	61	0.41
Field Tests on Prototype by Stantec Consulting Ltd 2001					
Prototype	-	743450	3500	212	0.67
for CR12	-		6000	124	0.72

Table 4-8. Summary of Travel Distance to Volume Ratio for the E.L Smith Model

Configuration	Experiment	Travel Distance (mm)	Water Depth (mm)	L/D	T_{10}/T_d
(1)	(2)	(3)	(4)	(5)	(6)
Phase 1: Model Confirmation					
CE1	E1	5460	89	61	0.17
	E2		82	66	0.20
	E3		86	63	0.17
	E4		86	63	0.20
	E5		82	66	0.18
Phase 2: Design Modifications					
CE2	E6	13030	82	159	0.74
	E7		82	159	0.68
	E8		86	151	0.75
	E9		86	151	0.68
CE3	E10	20590	82	251	0.83
	E11		82	251	0.89
	E12		86	239	0.90
	E13		86	239	0.90
Field Tests on Prototype by Liem 1994 in model equivalent values					
CE1	-	259896	4100	63	0.27
	-		3900	67	0.19

Table 4-9. Comparison of USEPA's Guidance Manual Baffling Classification to Model Study Results

Baffling Condition (1)	T_{10}/T_d (2)	Baffling Description (3)	Configurations (4)	Measured T_{10}/T_d (5)
Unbaffled (mixed flow)	0.1	None, agitated basin, very low length to width ratio, high inlet and outlet flow velocities		
Poor	0.3	Single or multiple unbaffled inlets and outlets, no intra-basin baffles	CR1, CR2, CE1	0,17 - 0,25
Average	0.5	Baffled inlet or outlet with some intra-basin baffles	CR3, CR9	0,35 - 0,42
Superior	0.7	Perforated inlet baffle, serpentine or perforated intra-basin baffles, outlet weir or perforated launders	CR4, CR5, CR6, CR7, CR8, CR10 CR11, CR12, CE2, CE3	0,5 - 0,9
Perfect (plug flow)	1.0	Very high length to width ratio (pipeline flow), perforated inlet, outlet, and intra-basin baffles		

Table 4-10. Summary of Experiments with Variable Discharges

Configuration (1)	Experiment (2)	Qm (L/min) (3)	Depth (mm) (4)	T_{10} (min) (5)	T_{10}/T_d (6)
CR1	R1	29.1	273	46	0.25
	R2			46	0.25
	R3	14.5		84	0.23
CR6	R17	48.5	239	75	0.79
	R18	38.8		97	0.82
	R15	29.1		105	0.66
	R16	9.7		265	0.56
CR7	R20	58.2	239	63	0.79
	R22	38.8		95	0.80
	R19	29.1		118	0.74
	R21	29.1		118	0.74
CR9*	R25	58.2	239	17	0.42
	R24	41.7		21	0.36
CR11	R27	58.2	239	52	0.64
	R28			47	0.58
	R29	29.1		93	0.57
CR12	R30	58.2	239	49	0.61
	R31	29.1		113	0.70

* Tests in CR9 were conducted in the east cell only.

Figure 4-1. Comparison of Prototype and Model F-curves for Rossdale System at Q = 150 ML/d

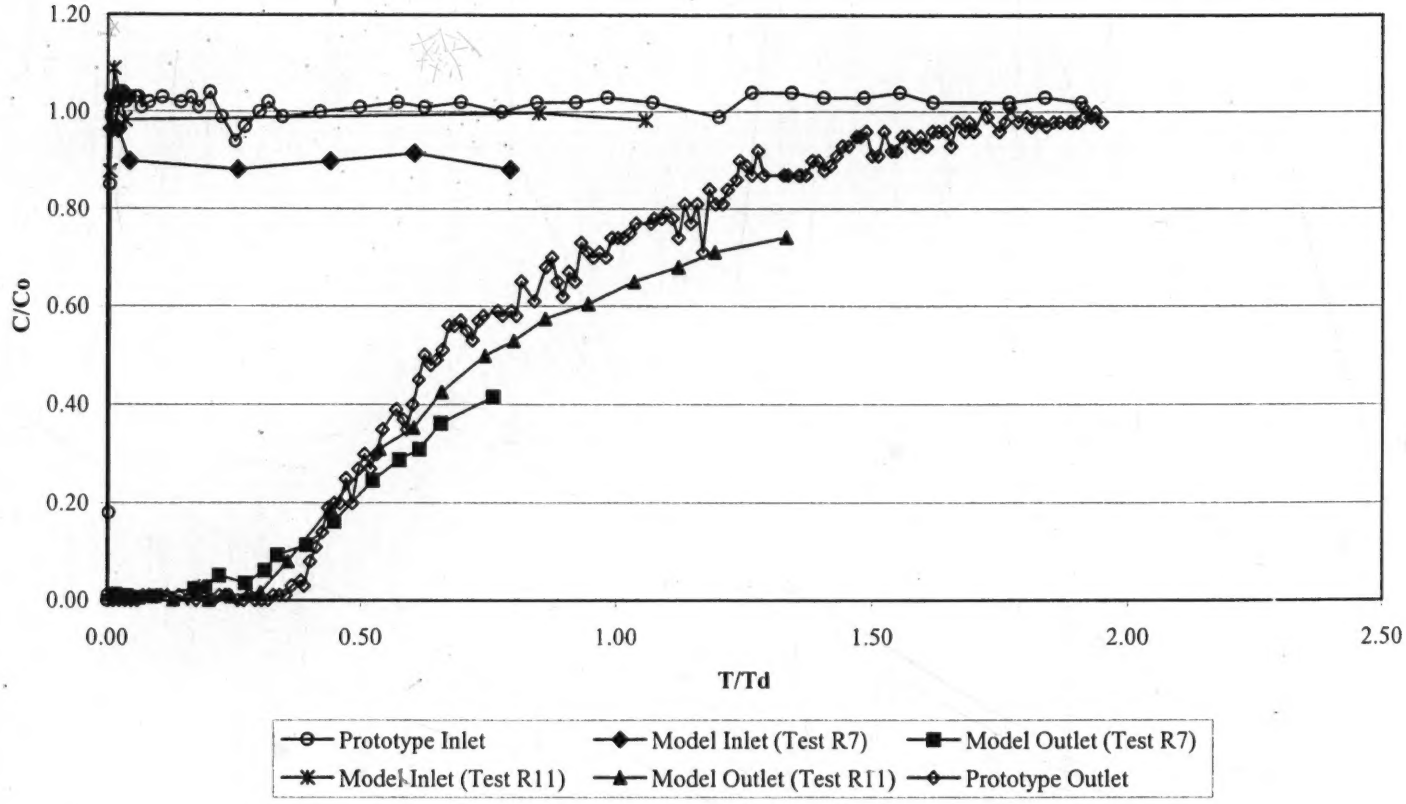


Figure 4-2. Comparison of Prototype and Model F-curves for Rossdale System at Q = 130 ML/d

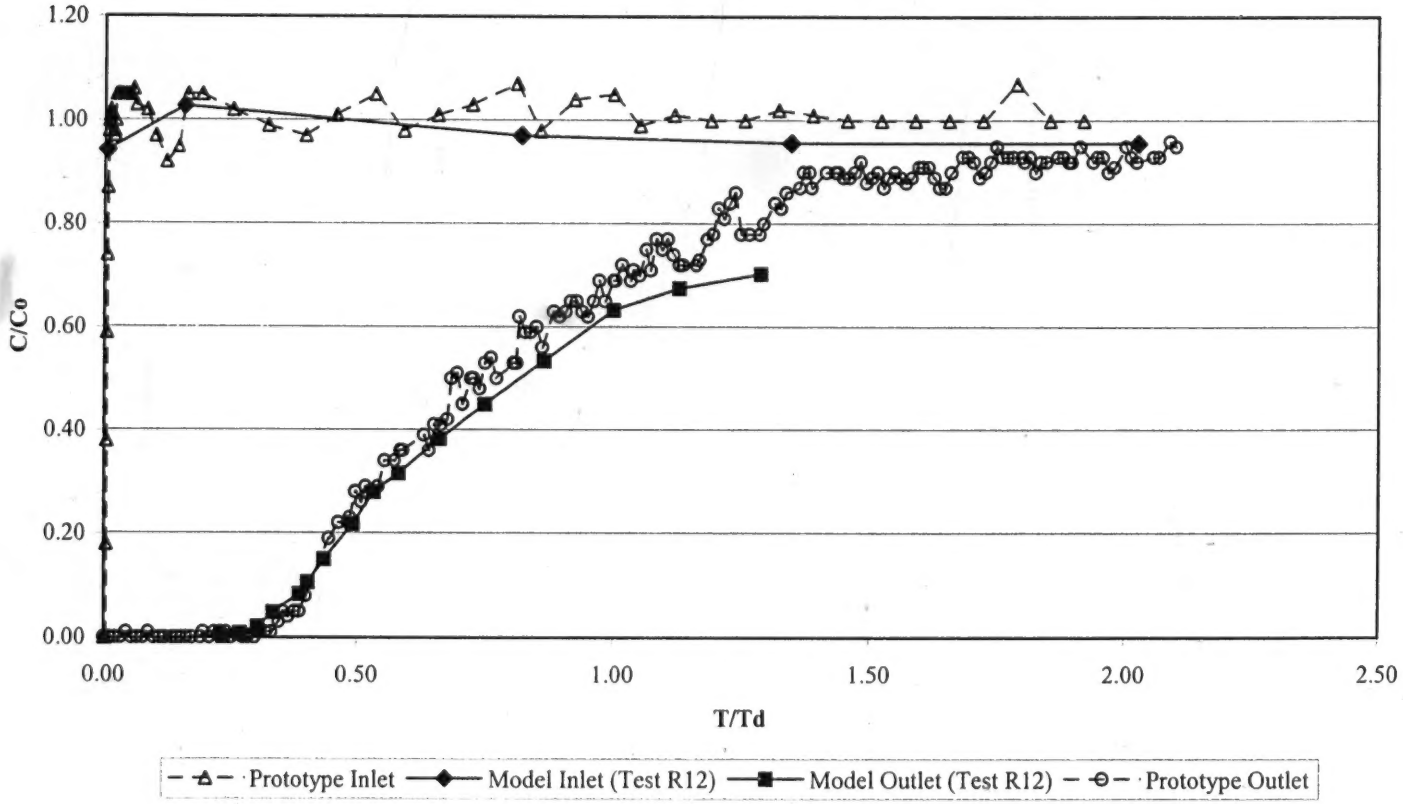


Figure 4-3. Comparison of Prototype and Model F-curves for Rossdale's East Cell at Q = 150 ML/d

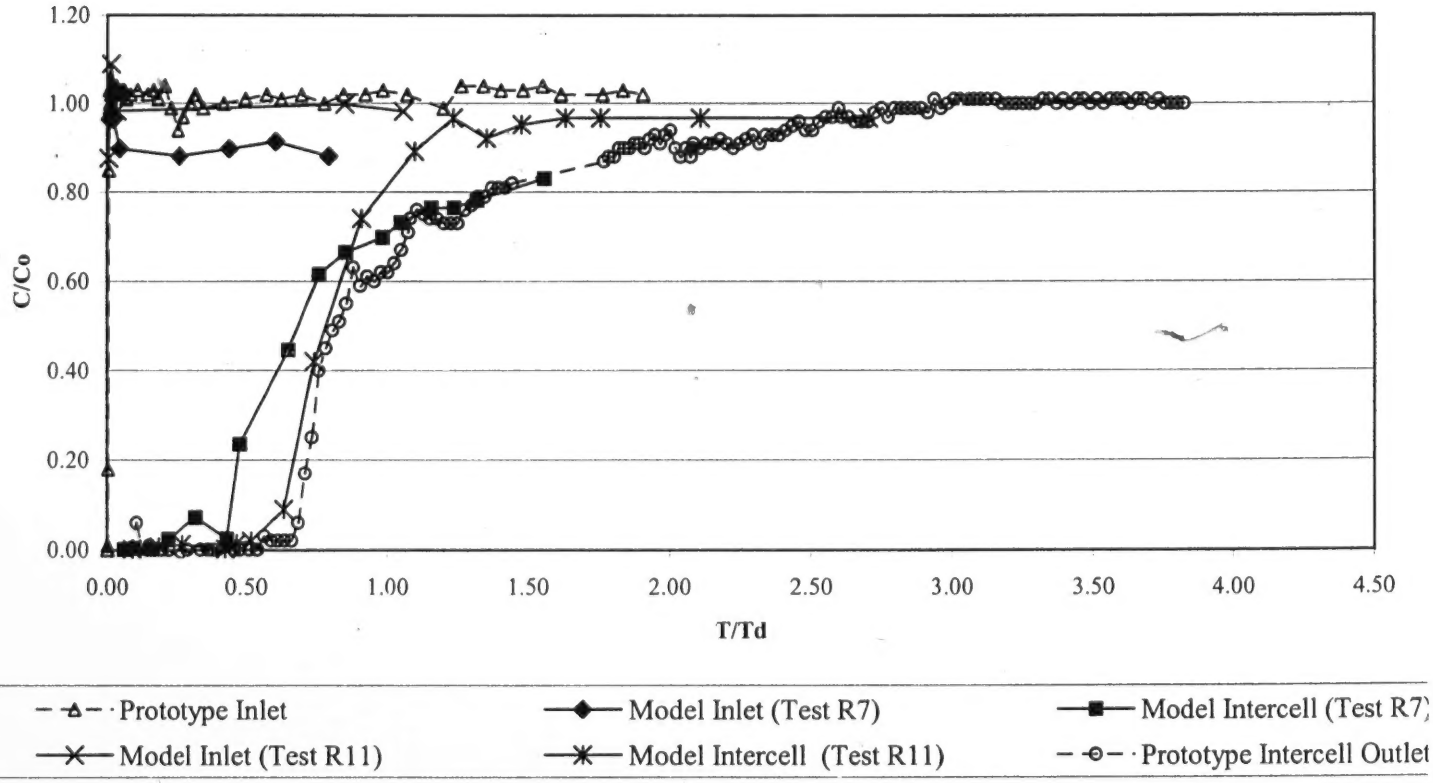


Figure 4-4. Comparison of Prototype and Model F-curves for Rossdale's East Reservoir at Q = 130 ML/d

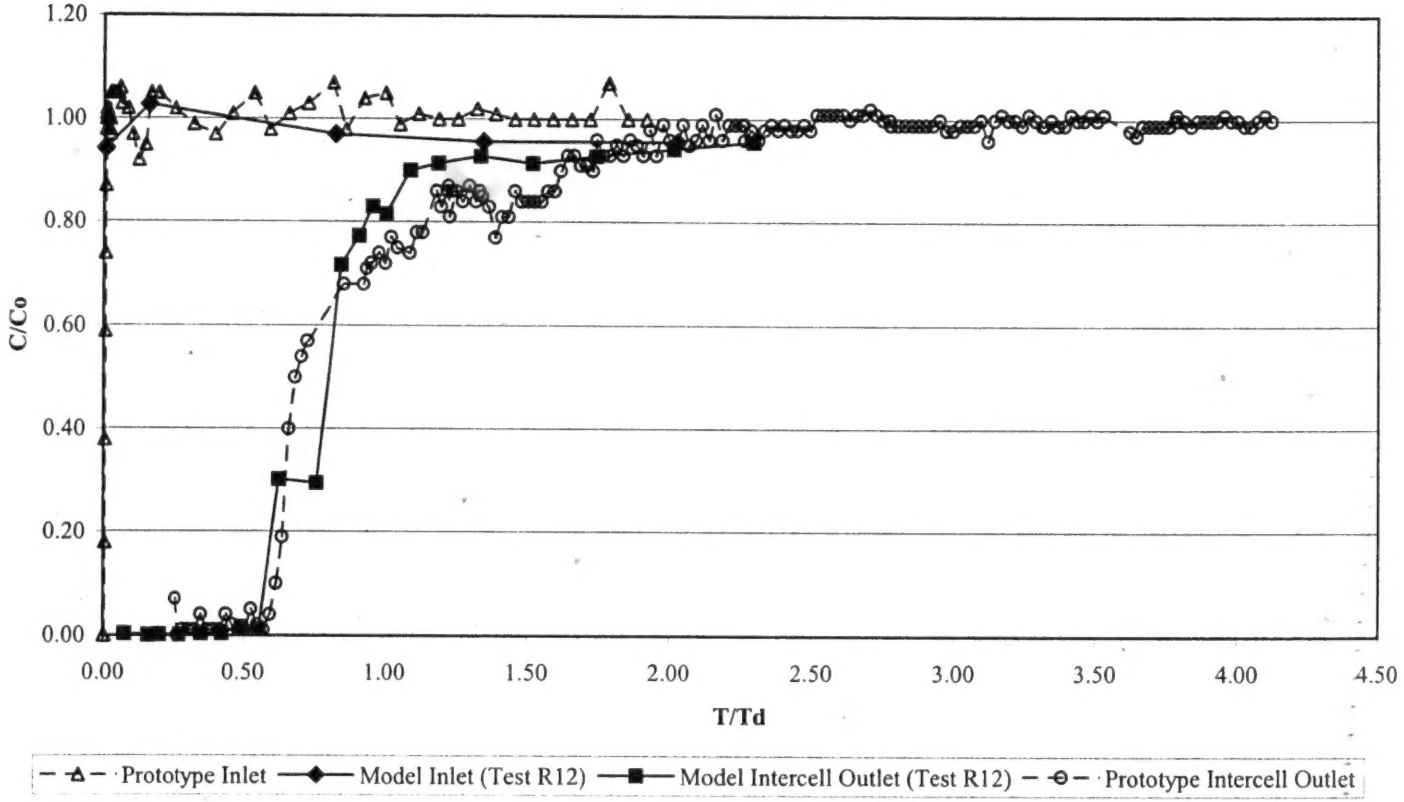


Figure 4-5. Comparison of Prototype and Model F-curves for E.L. Smith Reservoir at Q = 180 ML/d

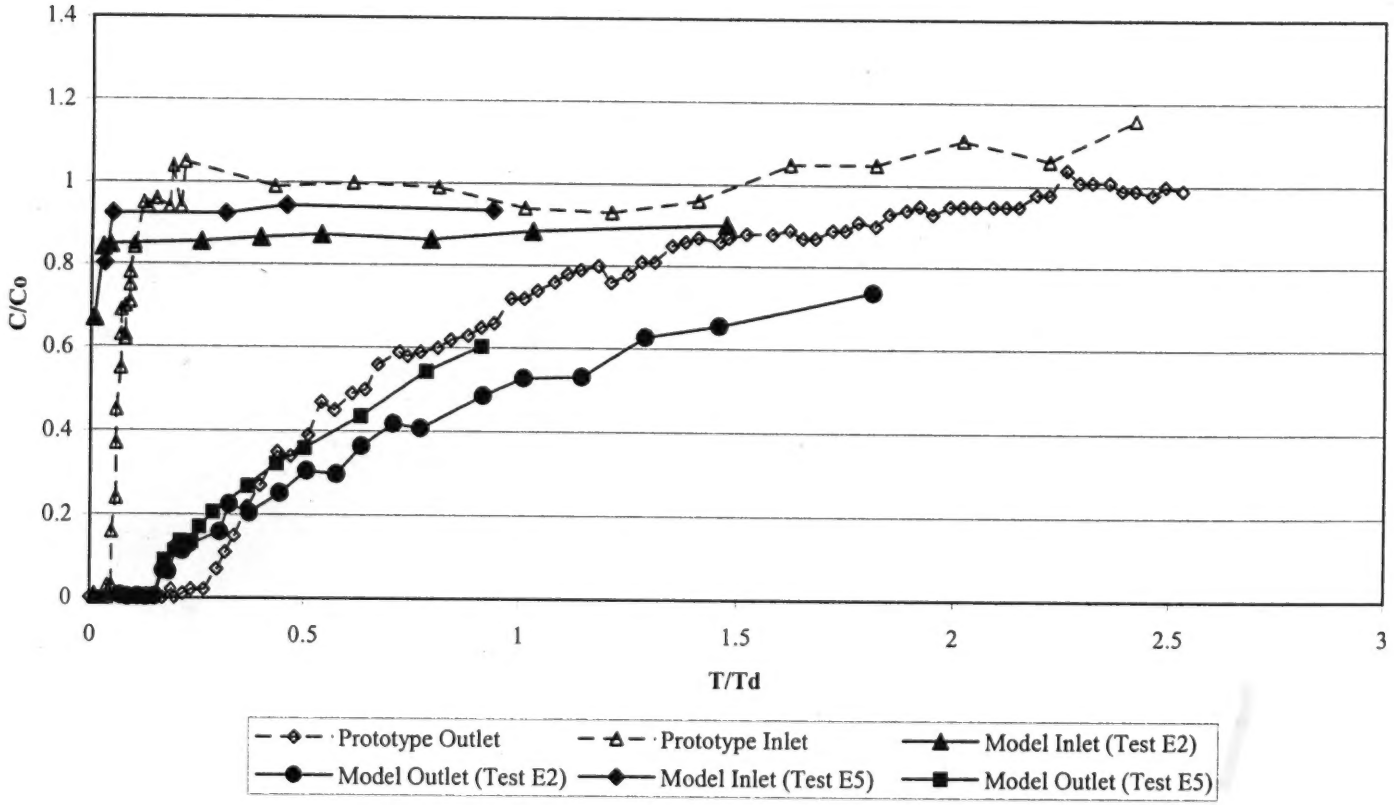


Figure 4-6. Comparison of Prototype and Model F-curves for E.L. Smith Reservoir at Q = 230 ML/d

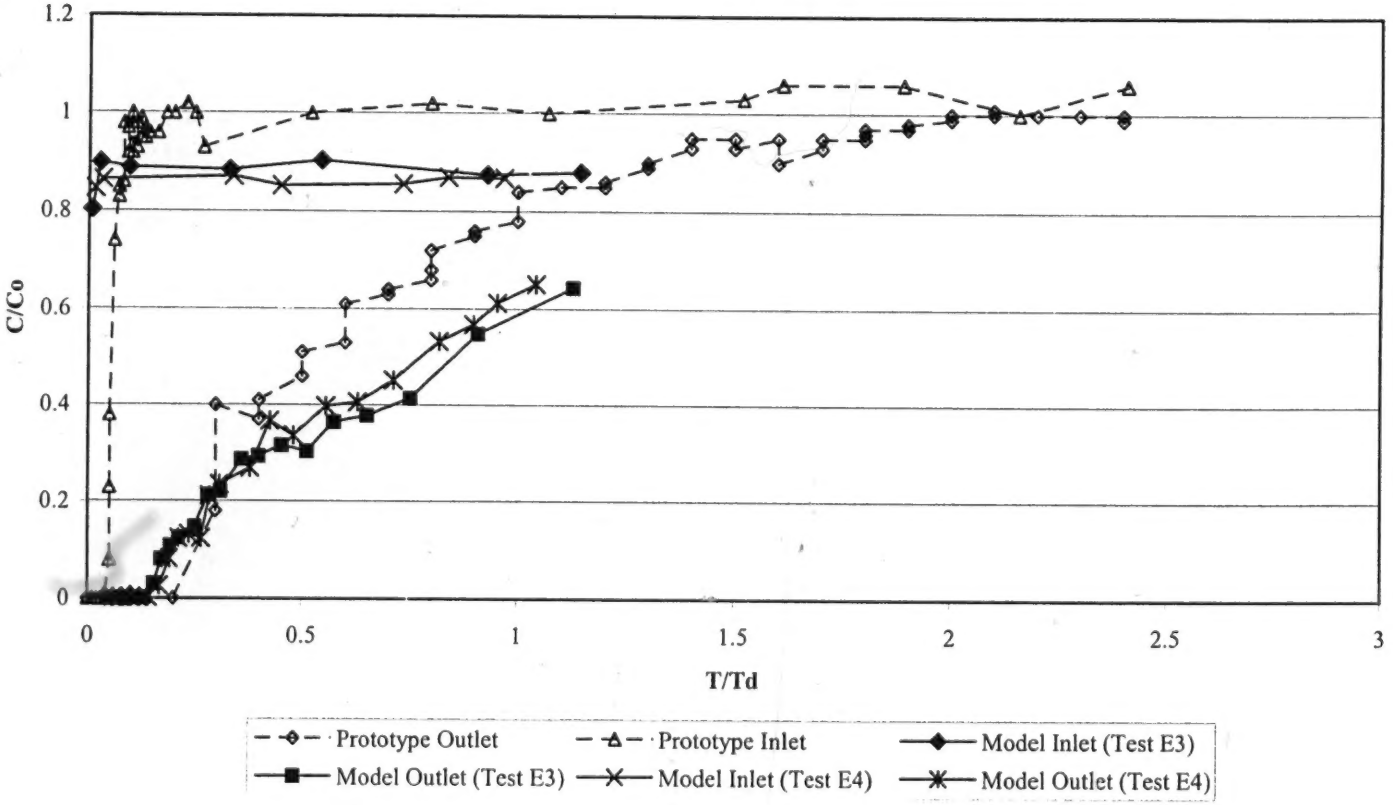


Figure 4-7. Dependence of Baffle Parameter on Length to Width Ratio

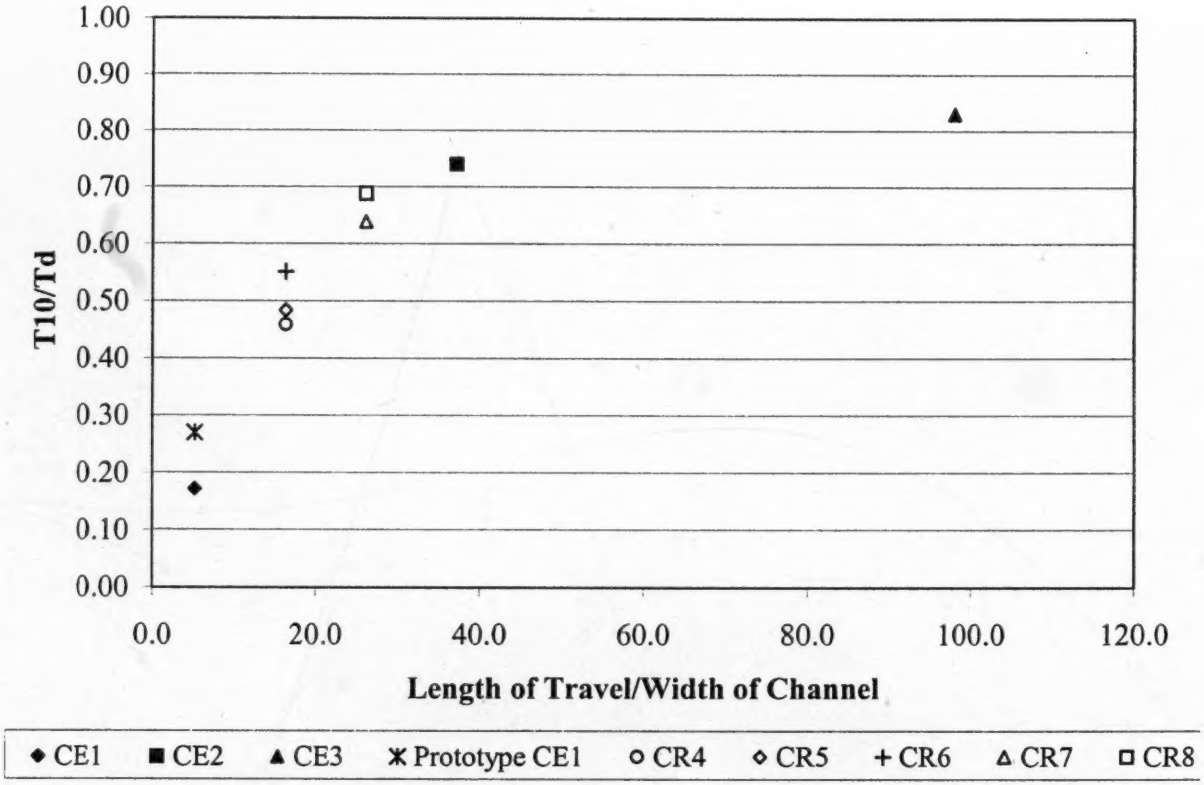


Figure 4-8. F-Curve Progression with Addition of Baffle Walls in E.L. Smith Model (Q = 8.1 L/min)

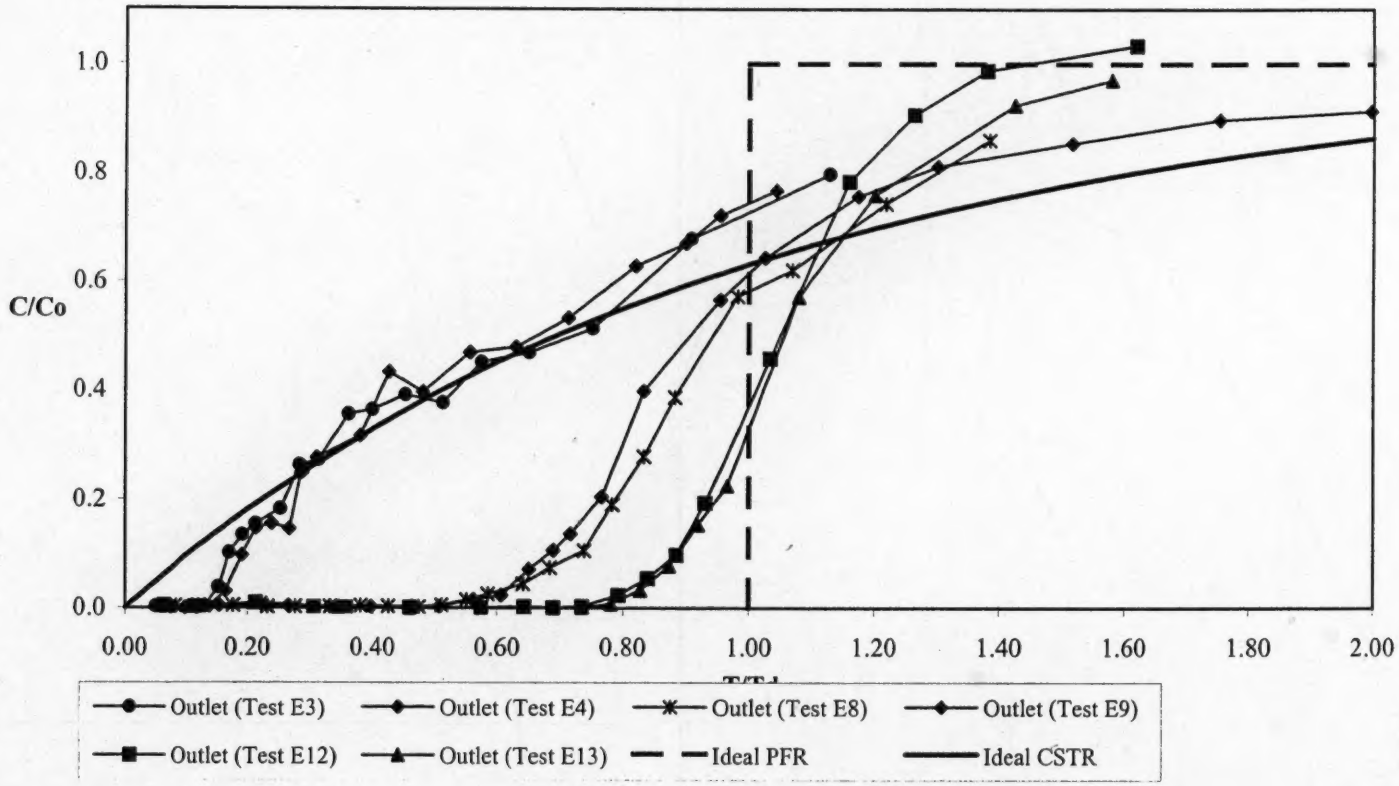


Figure 4-9. F-Curve Progression with Addition of Baffle Walls in E.L. Smith Model (Q = 10.3 L/min)

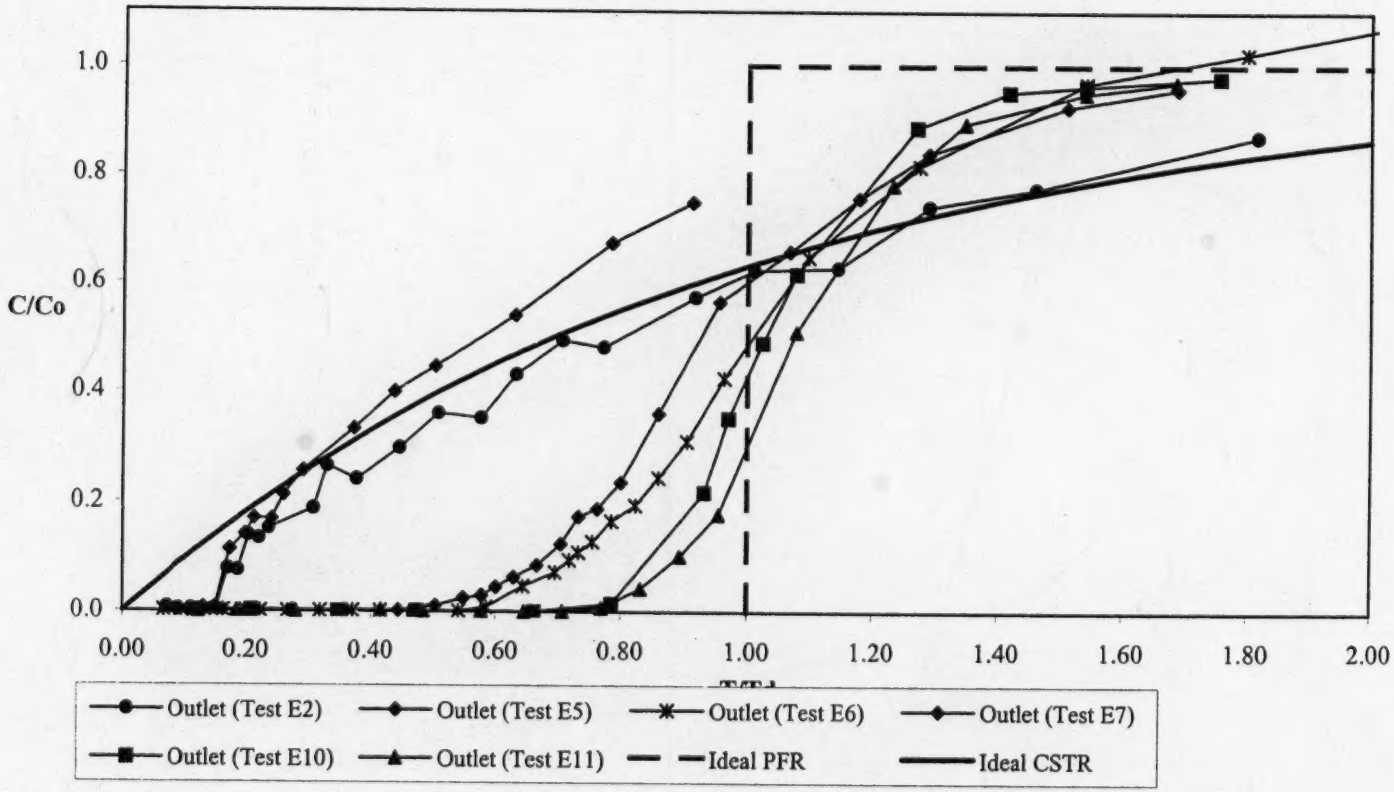
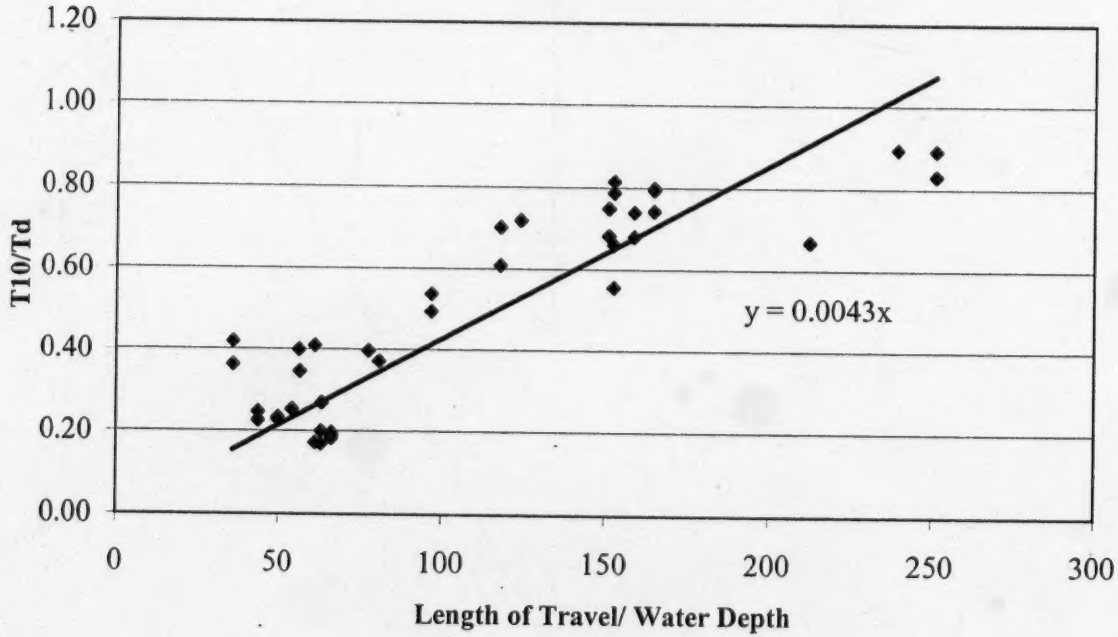
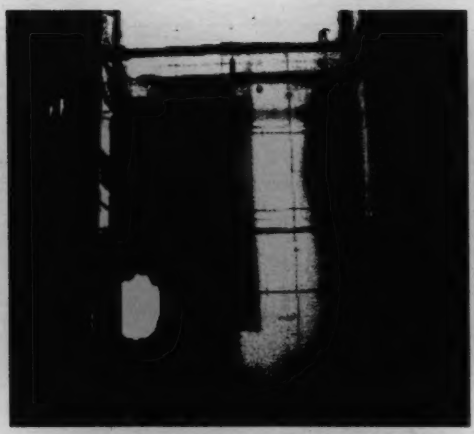


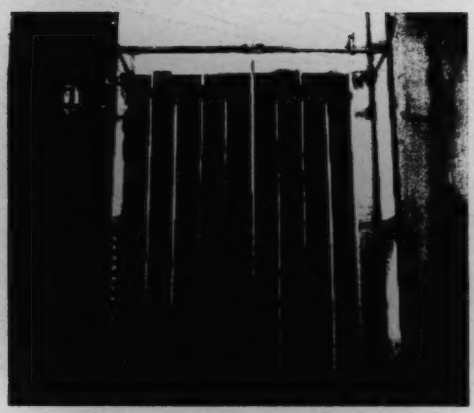
Figure 4-10. Dependence of Baffle Parameter on Travel Distance to Water Depth Ratio





1) View from above of the dye pattern in E.L. Smith model configuration CE1.

2) View from above of the dye pattern in E.L. Smith model configuration CE2.



3) View from above of the dye pattern in E.L. Smith model configuration CE3.

HYDRAULIC MODELLING OF STORAGE TANKS IN WATER DISTRIBUTION SYSTEMS

Dye Patterns for E.L. Smith Model Testing

PHOTO PLATE 4-1

5.0 Conclusions and Recommendations

5.1 Physical Models of Storage Tanks

A comparison was made between the T_{10}/T_d ratios and the F-curves resulting from tracer tests conducted in two full-scale storage tanks and the hydraulic models built to simulate them. This comparison was made to determine whether or not each physical model possesses equivalent hydraulic characteristics to the prototype tank that it represents. The length scale of the Rossdale model and the E.L. Smith model, which were both tested in this study, was 1:26.4 and 1:47.46, respectively. The results from the physical hydraulic models were comparable to the results of past tracer studies conducted in the prototype tanks by Liem et al (1997) and by Stantec Consulting Ltd (2001). It was concluded that hydraulic modelling using Froude criteria is an adequate method of studying the flow characteristics of storage reservoirs.

In terms of the T_{10}/T_d ratio, the results indicate that both the Rossdale model and the E.L. Smith model adequately simulate the flow patterns produced by the prototype reservoirs. By applying the techniques herein, the T_{10}/T_d ratio determined in both the models was within 10% of the prototype value.

The F-curves resulting from tracer tests in the prototype and the scale model of the Rossdale reservoir had good correlation. However, the point of tracer injection and the outflow concentration measurement locations for the E.L. Smith model were marginally different than those of the prototype. The shape of the model and prototype F-curves were relatively similar, but the difference in the sample points contributed to a slight discrepancy or shift in the curves. For a direct comparison of the F-curves, it is best to have equivalent locations for tracer injection and sample collection in the prototype and the model.

5.2 Considerations for the Design of Storage Tanks

One objective of this study was to collect and evaluate experimental data to assess the dependence of hydraulic performance on various design parameters such as the baffle wall arrangement and inlet design, and operational parameters such as the water depth and discharge. Tracer studies were used to determine the hydraulic efficiency of each tank configuration. Some of the important observations include:

- An increase in the length to width ratio (L:W) of the channels created by the addition of internal baffle walls result in an increase in the detention time for a storage tank. Significant increases in the T_{10}/T_d value occur up to a L:W of approximately 30:1.

- A general relationship can be developed between the fluid retention time and the ratio of travel distance to water depth within a tank. The relationship was found to be linear and equal to:

$$T_{10}/T_d = 0.0043(L:D)$$

  This relationship could be useful in estimating baffling requirements for various values of T_{10}/T_d.

- The results of this study indicate that the baffle parameter is overestimated in the USEPA Guidance Manual (1990) for the poor to average baffling conditions.

- A submerged pipe elbow directed down into a trench, as seen at the inlet to the actual Rossdale reservoir system, is an effective design in terms of dissipating the momentum of flow at the inlet and extending the fluid retention time for the tank.

- Flow diffuser pipes installed at the inlet of a storage tank can improve the lateral mixing above that of a simple circular influent pipe. However, pipe

diffusers were found to have little affect on the retention time for the tank unless aimed at an outer wall of the tank.

- A pipe elbow connected to the influent pipe, which directs fluid towards the outer wall of a storage tank is a simple and effective design for reducing the momentum of flow entering the tank and increasing the retention time.

- Observations of the effect of water level and discharge on the retention time were a secondary consideration and consequently limited. No apparent change in the baffle parameter was recorded for as much as a 30% change in the operating water level and observations regarding the effects of discharge were inconclusive. However, it was noted that the height of the baffle walls installed in a storage tank must exceed the operating water level to prevent flow from short-circuiting over the walls, and consequently reducing the retention time for portions of the tank's contents.

5.3 Recommendations for Future Research

This investigation provided knowledge into experimental test procedures and design techniques, which can be used towards improving the contact hydraulics of storage tanks at water treatment facilities. In addition, it has brought light to several new questions and ideas on the topic. The following recommendations should be considered for future research:

- The general relationship determined between the baffle parameter and the ratio of the travel distance divided by the water depth should be further scrutinised to develop a better understanding of its boundaries, such as the affect of the tank's width and length on the linear relationship.

- A more precise investigation of the flow entering storage tanks, which includes the measurement of concentration and velocity profiles would be very insightful and useful for the development of the inlet design.

- Knowledge into the effects of operational conditions such as water depth and discharge could be used as guidance for optimising the retention time for a particular tank design. For that reason, further research including a wider range of variations in the water level and in the discharge through a storage tank is advisable.

- The results of this study suggest that by applying a smaller discharge than that implied by the Froude criterion, when modelling a storage tank, a better representation of the hydraulic attributes of the storage tank may be reached. This concept is worthy of further investigation.

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Appendix A

Model Tracer Study
Experimental Data

Rossdale WTP Phase I

Test #R1 Date: 01/06/1998 Q= 29.1 L/min Co= 9.2

D= 273 mm Cback= 0.3 31.6

CR1

Inlet				Intercell Outlet				Outlet			
Time (min)	C	level	C/Co	Time (min)	C	level	C/Co	Time (min)	C	level	C/Co
1.50	9.2	1	1.00	8.50	8.7	31.6	0.03	17.50	4.0	31.6	0.01
2.00	9.1	1	0.99	9.98	1.5	3.16	0.05	21.00	6.3	31.6	0.02
3.00	9.2	1	1.00	10.50	2.7	3.16	0.09	27.00	1.0	3.16	0.03
4.50	9.1	1	0.99	11.83	2.9	3.16	0.10	33.50	1.6	3.16	0.05
6.50	9.1	1	0.99	13.33	3.7	3.16	0.13	39.50	2.1	3.16	0.07
11.60	9.0	1	0.98	15.42	3.9	3.16	0.13	47.77	3.2	3.16	0.11
22.22	9.0	1	0.98	19.75	4.9	3.16	0.17	53.33	3.8	3.16	0.13
30.17	8.9	1	0.97	23.75	6.3	3.16	0.22	60.00	4.4	3.16	0.15
42.00	8.9	1	0.97	28.50	7.7	3.16	0.26	70.00	5.8	3.16	0.20
84.58	9.1	1	0.99	31.83	8.2	3.16	0.28	92.16	7.3	3.16	0.25
				34.92	9.1	3.16	0.31				
				40.50	9.8	3.16	0.34				
				44.83	3.8	1	0.41				
				48.75	3.8	1	0.41				
				52.00	4.1	1	0.44				
				57.00	4.5	1	0.49				
				65.27	4.7	1	0.51				
				75.77	5.2	1	0.56				
				84.58	5.6	1	0.61				

Rossdale WTP Phase I

Test #R2 Date: 02/06/1998 Q= 29.1 L/min Co= 8.9

D= 273 mm Cback= 0.3 31.6

CR1

Inlet				Intercell Outlet				Outlet			
Time (min)	C	level	C/Co	Time (min)	C	level	C/Co	Time (min)	C	level	C/Co
0.67	8.9	1	1.00	4.50	1.4	31.6	0.00	17.37	5.0	31.6	0.02
1.00	9.1	1	1.02	7.42	1.1	31.6	0.00	22.35	8.9	31.6	0.03
1.50	9.2	1	1.03	8.92	5.7	31.6	0.02	29.00	1.3	3.16	0.05
2.58	9.2	1	1.03	10.00	6.7	31.6	0.02	32.55	1.8	3.16	0.06
5.78	9.1	1	1.02	11.67	2.6	3.16	0.09	36.28	2.3	3.16	0.08
16.00	9.0	1	1.01	13.30	2.5	3.16	0.09	41.77	2.4	3.16	0.08
29.75	9.0	1	1.01	18.93	4.3	3.16	0.15	48.45	3.2	3.16	0.11
42.75	8.9	1	1.00	20.56	5.0	3.16	0.18	54.50	3.8	3.16	0.13
52.50	8.9	1	1.00	25.43	6.6	3.16	0.23	60.50	4.9	3.16	0.17
86.57	9.1	1	1.02	31.17	8.6	3.16	0.30	63.33	5.1	3.16	0.18
108.00	9.0	1	1.01	33.82	8.6	3.16	0.30	68.55	5.5	3.16	0.19
				38.00	9.7	3.16	0.34	73.00	5.9	3.16	0.21
				40.50	3.2	1	0.36	80.67	7.2	3.16	0.25
				45.00	3.6	1	0.40	91.00	8.2	3.16	0.29
				56.00	4.0	1	0.45	96.00	8.6	3.16	0.30
				65.33	4.8	1	0.54	101.00	9.1	3.16	0.32
				74.00	5.2	1	0.58	107.00	3.2	1	0.36
				82.00	5.6	1	0.63	112.00	3.4	1	0.38
				92.00	5.9	1	0.66	117.00	3.5	1	0.39
				97.20	6.1	1	0.68	123.00	3.7	1	0.41
				102.00	6.2	1	0.70	127.75	3.9	1	0.44
				110.20	6.6	1	0.74				
				120.00	6.9	1	0.77				

Rossdale WTP Phase I

Test #R3 Date: 03/06/1998 Q= 14.5 L/min Co= 8.3

D= 273 mm Cback= 0.3 31.6

CR1

Inlet				Intercell Outlet				Outlet			
Time (min)	C	level	C/Co	Time (min)	C	level	C/Co	Time (min)	C	level	C/Co
0.33	8.3	1	1.00	7.50	0.3	31.6	0.00	24.75	5.2	31.6	0.02
0.80	8.7	1	1.05	11.67	2.3	31.6	0.01	33.25	5.6	31.6	0.02
1.50	8.8	1	1.06	15.00	7.2	31.6	0.03	40.75	8.6	31.6	0.03
2.50	8.8	1	1.06	17.00	8.8	31.6	0.03	49.83	1.2	3.16	0.04
5.18	8.8	1	1.06	19.00	2.8	3.16	0.11	55.00	1.5	3.16	0.06
26.33	8.6	1	1.04	21.67	3.2	3.16	0.12	66.83	1.7	3.16	0.06
48.17	8.4	1	1.01	30.00	4.3	3.16	0.16	71.00	2.0	3.16	0.08
94.00	8.4	1	1.01	36.30	5.5	3.16	0.21	78.20	2.3	3.16	0.09
140.77	8.6	1	1.04	46.55	1.9	1	0.23	83.67	2.7	3.16	0.10
185.17	8.6	1	1.04	58.00	2.6	1	0.31	93.17	3.2	3.16	0.12
215.17	8.4	1	1.01	65.25	2.8	1	0.34	98.17	3.4	3.16	0.13
				72.17	3.0	1	0.36	103.00	3.7	3.16	0.14
				85.17	3.2	1	0.38	108.50	3.8	3.16	0.14
				91.80	3.6	1	0.43	120.50	4.7	3.16	0.18
				97.00	3.7	1	0.44	132.60	5.1	3.16	0.19
				104.17	4.0	1	0.48	139.17	1.7	1	0.20
				110.00	4.1	1	0.49	147.60	6.0	3.16	0.23
				119.33	4.3	1	0.52	161.65	6.9	3.16	0.26
				134.83	4.9	1	0.59	171.00	7.7	3.16	0.29
				151.00	5.1	1	0.61	181.50	8.0	3.16	0.30
				163.72	5.6	1	0.67	193.00	8.6	3.16	0.33
				183.00	5.7	1	0.69	200.50	9.1	3.16	0.35
				198.50	5.9	1	0.71	210.00	9.5	3.16	0.36
				224.67	5.9	1	0.71	223.70	3.3	1	0.40

Rossdale WTP Phase I

Test #R4 Date: 05/06/1998 Q= 29.1 L/min Co= 8.4

D= 239 mm Cback= 0.2 31.6

CR1

Inlet				Intercell Outlet				Outlet			
Time (min)	C	level	C/Co	Time (min)	C	level	C/Co	Time (min)	C	level	C/Co
0.53	8.4	1	1.00	4.27	2.7	31.6	0.01	12.00	2.2	31.6	0.01
1.00	8.6	1	1.02	8.58	1.7	3.16	0.06	17.00	6.8	31.6	0.02
2.00	8.6	1	1.02	9.67	1.4	3.16	0.05	20.17	1.1	3.16	0.04
3.08	8.7	1	1.03	13.00	3.5	3.16	0.13	25.00	1.3	3.16	0.05
5.18	8.7	1	1.03	15.00	3.7	3.16	0.14	28.50	1.7	3.16	0.06
10.58	8.4	1	1.00	18.67	5.1	3.16	0.19	35.17	2.4	3.16	0.09
33.17	8.2	1	0.98	22.32	6.3	3.16	0.24	42.75	3.2	3.16	0.12
67.33	8.3	1	0.99	27.17	7.2	3.16	0.27	46.00	3.5	3.16	0.13
87.83	8.2	1	0.98	31.58	8.0	3.16	0.30	54.83	4.3	3.16	0.16
107.17	8.1	1	0.96	36.18	3.2	1	0.38	58.00	5.2	3.16	0.20
115.18	8.1	1	0.96	44.00	3.6	1	0.43	63.33	6.1	3.16	0.23
125.50	8.0	1	0.95	51.17	4.0	1	0.48	68.88	6.6	3.16	0.25
				55.95	4.5	1	0.53	75.75	7.7	3.16	0.29
				62.42	4.7	1	0.56	81.00	8.2	3.16	0.31
				70.00	5.1	1	0.61	89.25	2.9	1	0.34
				77.00	5.4	1	0.64	97.25	3.3	1	0.39
				84.00	5.6	1	0.67	106.58	3.5	1	0.42
				90.50	5.8	1	0.69	112.88	3.8	1	0.45
				98.33	6.2	1	0.74	123.00	4.1	1	0.49
				111.50	6.5	1	0.77	127.00	4.2	1	0.50
				124.50	6.8	1	0.81	130.50	4.4	1	0.52
				128.50	6.9	1	0.82				

Rossdale WTP Phase I

Test #R5 Date: 08/06/1998 Q= 29.1 L/min Co= 7.6

D= 220 mm Cback= 0.2 31.6

CR1

Inlet				Intercell Outlet				Outlet			
Time (min)	C	level	C/Co	Time (min)	C	level	C/Co	Time (min)	C	level	C/Co
0.40	7.6	1	1.00	5.43	0.9	31.6	0.00	15.30	6.0	31.6	0.02
1.00	7.8	1	1.03	9.37	1.5	3.16	0.06	21.83	8.7	31.6	0.04
2.00	7.8	1	1.03	13.97	3.1	3.16	0.13	26.83	1.5	3.16	0.06
4.00	7.7	1	1.01	25.5	6.5	3.16	0.27	31.00	1.9	3.16	0.08
12.17	7.7	1	1.01	29.75	7.8	3.16	0.32	33.50	1.9	3.16	0.08
27.75	7.4	1	0.97	34.5	8.6	3.16	0.36	35.75	2.2	3.16	0.09
47.25	7.2	1	0.95	90.75	5.4	1	0.71	38.00	2.5	3.16	0.10
62.25	7.2	1	0.95	97.25	5.5	1	0.72	39.75	2.7	3.16	0.11
100.75	7.4	1	0.97	102.17	5.9	1	0.78	41.50	2.8	3.16	0.12
114.75	7.4	1	0.97	109.75	5.9	1	0.78	43.50	3.0	3.16	0.12
				116.25	6.2	1	0.81	46.00	3.3	3.16	0.14
				122.58	6.1	1	0.80	48.50	3.8	3.16	0.16
								54.25	4.3	3.16	0.18
								60.00	4.9	3.16	0.20
								68.00	5.9	3.16	0.24
								73.75	6.7	3.16	0.28
								82.08	7.8	3.16	0.32
								89.00	8.4	3.16	0.35
								99.67	9.7	3.16	0.40
								108.75	3.5	1	0.46
								118.00	3.7	1	0.49
								124.00	4.0	1	0.53

Rossdale WTP Phase I

Test #R6 Date: 11/06/1998 Q= 29.1 L/min Co= 7.3

D= 239 mm Cback= 0.2 31.6

CR2

Inlet				Intercell Outlet				Outlet			
Time (min)	C	level	C/Co	Time (min)	C	level	C/Co	Time (min)	C	level	C/Co
0.50	7.3	1	1.00	8.33	0.3	31.6	0.00	16.00	4.5	31.6	0.02
1.50	7.3	1	1.00	9.50	1.6	3.16	0.07	19.00	6.0	31.6	0.03
2.50	7.4	1	1.01	11.25	1.4	3.16	0.06	22.00	0.9	3.16	0.04
4.00	7.5	1	1.03	20.00	5.3	3.16	0.23	27.25	1.4	3.16	0.06
28.42	7.1	1	0.97	24.00	6.6	3.16	0.29	33.00	1.8	3.16	0.08
67.50	7.1	1	0.97	30.00	7.8	3.16	0.34	36.00	2.2	3.16	0.09
				34.00	8.3	3.16	0.36	40.38	2.7	3.16	0.12
				37.88	9.1	3.16	0.39	41.50	2.8	3.16	0.12
				46.50	3.2	1	0.44	44.33	3.4	3.16	0.15
				52.00	3.7	1	0.51	47.80	3.5	3.16	0.15
				58.00	4.1	1	0.56	54.50	4.0	3.16	0.17
				64.53	4.2	1	0.57	61.40	4.8	3.16	0.21
				72.00	4.6	1	0.63	66.00	1.6	1	0.22
								73.78	1.9	1	0.26

Rossdale WTP Phase I

Test #R7 Date: 18/06/1998 Q= 29.1 L/min Co= 5.8

D= 239 mm Cback= 0.3 31.6

CR3

Inlet				Intercell Outlet				Outlet			
Time (min)	C	level	C/Co	Time (min)	C	level	C/Co	Time (min)	C	level	C/Co
1.25	5.8	1	1.00	4.75	0.6	31.6	0.00	2.57	2.7	31.6	0.01
3.23	5.8	1	1.00	8.00	1.1	31.6	0.00	6.12	2.1	31.6	0.01
7.00	5.4	1	0.93	12.75	0.7	31.6	0.00	10.00	1.4	31.6	0.01
41.87	5.3	1	0.91	17.72	4.9	31.6	0.03	14.83	1.9	31.6	0.01
70.87	5.4	1	0.93	26.00	1.4	3.16	0.07	27.67	4.8	31.6	0.02
97.25	5.5	1	0.95	35.00	0.5	3.16	0.03	31.50	5.5	31.6	0.03
127.67	5.3	1	0.91	38.67	4.5	3.16	0.24	36.00	1.0	3.16	0.05
				52.58	8.5	3.16	0.46	44.50	0.7	3.16	0.04
				61.50	3.7	1	0.64	50.50	1.2	3.16	0.06
				69.17	4.0	1	0.69	54.50	1.8	3.16	0.10
				79.63	4.2	1	0.72	63.50	2.2	3.16	0.12
				85.00	4.4	1	0.76	72.27	3.1	3.16	0.17
				93.75	4.6	1	0.79	84.25	4.7	3.16	0.25
				100.25	4.6	1	0.79	92.75	5.5	3.16	0.30
				106.75	4.7	1	0.81	99.00	5.9	3.16	0.32
				126.28	5.0	1	0.86	105.75	6.9	3.16	0.37
								122.50	2.5	1	0.43

Rossdale WTP Phase I

Test #R8 Date: 23/06/1998 Q= 58.2 L/min Co= 6.8

D= 239 mm Cback= 0.2 31.6

CR3

Inlet				Intercell Outlet				Outlet			
Time (min)	C	level	C/Co	Time (min)	C	level	C/Co	Time (min)	C	level	C/Co
1.08	6.8	1	1.00	2.00	1.7	31.6	0.01	4.58	1.7	31.6	0.01
3.28	7.0	1	1.03	2.42	3.0	31.6	0.01	8.67	1.8	31.6	0.01
15.27	6.6	1	0.97	5.60	8.2	31.6	0.04	12.17	2.4	31.6	0.01
47.38	6.6	1	0.97	7.50	7.9	31.6	0.04	19.00	1.2	31.6	0.00
73.17	6.5	1	0.95	10.33	2.2	3.16	0.10	23.60	1.0	31.6	0.00
				13.75	4.0	3.16	0.19	28.60	0.5	3.16	0.02
				17.68	3.8	3.16	0.18	33.00	0.6	3.16	0.03
				22.00	4.9	3.16	0.23	38.43	2.0	3.16	0.09
				27.00	4.6	3.16	0.21	46.70	2.1	3.16	0.10
				37.00	6.5	3.16	0.30	55.50	9.6	3.16	0.45
				45.30	7.5	3.16	0.35	60.00	5.5	3.16	0.26
				51.50	8.2	3.16	0.38	62.82	7.5	3.16	0.35
				56.75	9.0	3.16	0.42	72.08	8.5	3.16	0.39
				65.22	3.2	1	0.47	75.83	3.2	1	0.47
				70.67	3.4	1	0.50				
				74.67	3.4	1	0.50				

Rossdale WTP Phase 1

Test #R9 Date: 24/06/1998 Q= 58.2 L/min Co= 6.4

D= 265 mm Cback= 0.3 31.6

CR3

Inlet				Intercell				Outlet			
Time (min)	C	level	C/Co	Time (min)	C	level	C/Co	Time (min)	C	level	C/Co
1.42	6.4	1	1.00	4.92	1.4	31.6	0.01	0.58	1.0	31.6	0.00
7.43	6.4	1	1.00	10.77	1.1	31.6	0.00	2.50	9.4	31.6	0.04
29.00	6.4	1	1.00	15.00	1.4	31.6	0.01	5.83	2.1	3.16	0.10
58.83	6.3	1	0.98	23.65	3.6	31.6	0.02	9.17	2.4	3.16	0.12
				30.92	2.1	3.16	0.10	13.60	3.7	3.16	0.18
				37.67	3.8	3.16	0.19	19.53	4.2	3.16	0.21
				45.00	8.7	3.16	0.43	26.42	5.1	3.16	0.25
				56.25	3.7	1	0.58	32.00	6.2	3.16	0.31
				66.50	3.6	1	0.56	38.50	7.0	3.16	0.34
								46.67	8.0	3.16	0.39
								54.92	8.8	3.16	0.43
								65.50	3.2	1	0.50

Rossdale WTP Phase 1

Test #R10 Date: 26/06/1998 Q= 58.8 L/min Co= 7.3

D= 239 mm Cback= 0.3 31.6

CR3

Inlet				Intercell				Outlet			
Time (min)	C	level	C/Co	Time (min)	C	level	C/Co	Time (min)	C	level	C/Co
1.55	7.3	1	1.00	7.33	0.6	31.6	0.00	0.83	1.6	31.6	0.01
5.77	7.3	1	1.00	10.00	0.5	31.6	0.00	3.75	1.0	3.16	0.04
17.35	7.2	1	0.99	14.43	3.0	31.6	0.01	9.33	2.0	3.16	0.09
29.00	7.0	1	0.96	18.52	0.6	31.6	0.00	12.28	3.1	3.16	0.13
45.55	7.1	1	0.97	23.00	0.7	31.6	0.00	15.78	3.6	3.16	0.15
73.95	7.1	1	0.97	27.50	7.1	3.16	0.31	21.03	4.6	3.16	0.20
				33.72	9.1	3.16	0.39	25.00	5.4	3.16	0.23
				40.67	3.9	1	0.53	30.75	6.9	3.16	0.30
				50.00	3.9	1	0.53	35.52	7.3	3.16	0.32
				53.88	4.3	1	0.59	43.50	8.9	3.16	0.38
				59.00	4.0	1	0.55	48.30	3.2	1	0.44
				64.17	4.1	1	0.56	56.33	3.4	1	0.46
				68.63	4.6	1	0.63	61.42	4.0	1	0.55
								67.00	4.2	1	0.57
								73.00	4.1	1	0.56

Rossdale WTP Phase I

Test #R11 Date: 29/06/1998 Q= 29.1 L/min Co= 5.8

D= 167 mm Cback= 0.3 31.6

CR3

Inlet				Intercell Outlet				Outlet			
Time (min)	C	level	C/Co	Time (min)	C	level	C/Co	Time (min)	C	level	C/Co
0.42	5.8	1	1.00	4.95	0.7	31.6	0.00	14.62	0.7	31.6	0.00
1.33	7.2	1	1.24	10.33	1.7	31.6	0.01	22.92	0.4	31.6	0.00
3.83	6.5	1	1.12	15.18	2.8	31.6	0.01	28.00	1.9	31.6	0.01
96.00	6.6	1	1.14	23.82	0.7	31.6	0.00	34.48	3.7	31.6	0.02
119.50	6.5	1	1.12	26.13	3.3	31.6	0.02	40.50	1.7	3.16	0.09
				29.00	4.4	31.6	0.02	49.93	4.0	3.16	0.22
				35.50	1.9	3.16	0.10	60.67	6.5	3.16	0.35
				41.50	8.8	3.16	0.48	68.20	7.4	3.16	0.40
				50.90	4.9	1	0.84	74.50	8.9	3.16	0.48
				61.50	5.9	1	1.02	84.17	3.3	1	0.57
				69.17	6.4	1	1.10	90.50	3.5	1	0.60
				75.75	6.1	1	1.05	97.50	3.8	1	0.65
				82.75	6.3	1	1.08	107.00	4.0	1	0.69
				91.50	6.4	1	1.10	117.00	4.3	1	0.74
				98.50	6.4	1	1.10	126.73	4.5	1	0.77
				118.00	6.4	1	1.10	134.62	4.7	1	0.81
				151.43	6.4	1	1.10	150.42	4.9	1	0.84

Rossdale WTP Phase I

Test #R12 Date: 02/07/1998 Q= 23.5 L/min Co= 6.7

D= 174 mm Cback= 0.2 31.6

CR3

Inlet				Intercell Outlet				Outlet			
Time (min)	C	level	C/Co	Time (min)	C	level	C/Co	Time (min)	C	level	C/Co
0.72	6.7	1	1.00	5.43	1.0	31.6	0.00	34.75	0.6	31.6	0.00
23.33	7.3	1	1.09	11.57	0.3	31.6	0.00	39.50	2.1	31.6	0.01
60.00	6.9	1	1.03	14.50	0.6	31.6	0.00	44.50	4.9	31.6	0.02
98.35	6.8	1	1.01	19.90	0.5	31.6	0.00	49.00	1.1	3.16	0.05
148.00	6.8	1	1.01	25.67	0.9	31.6	0.00	56.50	1.9	3.16	0.09
				31.00	1.1	31.6	0.00	59.00	2.4	3.16	0.11
				36.00	3.8	31.6	0.02	63.62	3.4	3.16	0.16
				40.50	3.0	31.6	0.01	71.80	4.9	3.16	0.23
				45.50	6.8	3.16	0.32	77.87	6.3	3.16	0.30
				55.25	2.1	1	0.31	85.00	7.1	3.16	0.33
				61.48	5.1	1	0.76	96.72	8.6	3.16	0.41
				66.25	5.5	1	0.82	109.62	3.2	1	0.48
				69.73	5.9	1	0.88	126.52	3.8	1	0.57
				73.28	5.8	1	0.86	146.17	4.5	1	0.67
				79.50	6.4	1	0.95	164.72	4.8	1	0.72
				86.70	6.5	1	0.97	188.20	5.0	1	0.75
				97.58	6.6	1	0.98				
				110.83	6.5	1	0.97				
				127.20	6.6	1	0.98				
				147.00	6.7	1	1.00				
				167.40	6.8	1	1.01				

Rossdale WTP Phase II

Test #R13 Date: 10/07/1998 Q= 29.1 L/min Co= 8.8

D= 239 mm Cback= 0.3 31.6

CR4

Inlet				Intercell Outlet				Outlet			
Time (min	C	level	C/Co	Time (min	C	level	C/Co	Time (min	C	level	C/Co
0.43	8.8	1	0.999	6.27	0.6	31.6	0.001	7.50	0.5	31.6	0.001
1.17	8.9	1	1.010	13.17	0.4	31.6	0.000	19.43	2.2	31.6	0.007
3.60	8.9	1	1.010	21.30	0.4	31.6	0.000	28.18	0.9	31.6	0.002
22.67	8.6	1	0.976	27.17	1.6	31.6	0.005	35.83	1.5	31.6	0.004
46.00	8.2	1	0.931	34.00	1.7	3.16	0.060	44.00	0.4	31.6	0.000
88.42	8.3	1	0.942	39.80	3.9	3.16	0.139	52.25	0.6	31.6	0.001
120.00	8.3	1	0.942	44.75	5.2	3.16	0.186	55.50	0.7	31.6	0.001
				51.00	9.0	3.16	0.323	59.83	5.7	31.6	0.019
				56.25	3.8	1	0.431	65.50	3.1	31.6	0.010
				61.25	3.9	1	0.442	69.50	8.7	31.6	0.030
				66.33	4.9	1	0.556	73.50	1.5	3.16	0.053
				72.33	5.0	1	0.567	80.25	2.9	3.16	0.103
				82.00	6.3	1	0.715	85.50	3.0	3.16	0.107
				87.42	6.7	1	0.760	98.00	2.0	1	0.226
				91.77	7.0	1	0.794	102.40	2.3	1	0.260
				99.00	7.1	1	0.806	108.28	2.6	1	0.294
				104.73	7.2	1	0.817	113.00	3.1	1	0.351
				111.95	7.6	1	0.863	118.67	3.6	1	0.408
				119.33	7.8	1	0.885	125.65	3.8	1	0.431

Rossdale WTP Phase II

Test #R14 Date: 14/07/1998 Q= 29.1 L/min Co= 6.5

D= 239 mm Cback= 0.2 31.6

CR5

Inlet				Intercell Outlet				Outlet			
Time (min	C	level	C/Co	Time (min	C	level	C/Co	Time (min	C	level	C/Co
1.00	6.5	1	0.999	6.25	0.6	31.6	0.002	13.00	0.4	31.6	0.001
1.75	7.7	1	1.184	11.50	0.6	31.6	0.002	20.40	0.5	31.6	0.001
3.50	7.8	1	1.199	16.50	0.6	31.6	0.002	29.50	0.4	31.6	0.001
7.00	7.6	1	1.168	23.28	0.3	31.6	0.000	41.83	0.3	31.6	0.000
23.83	7.4	1	1.137	27.92	0.3	31.6	0.000	51.50	0.3	31.6	0.000
113.00	7.5	1	1.153	32.77	0.7	31.6	0.002	56.70	0.3	31.6	0.000
140.50	7.6	1	1.168	37.50	1.0	3.16	0.048	61.63	0.3	31.6	0.000
				39.50	2.5	3.16	0.121	68.60	1.0	31.6	0.004
				42.75	2.2	3.16	0.106	73.77	2.9	31.6	0.013
				47.25	5.4	3.16	0.262	79.87	1.0	3.16	0.048
				52.25	7.0	3.16	0.340	82.60	1.1	3.16	0.053
				66.25	4.2	1	0.645	86.33	2.0	3.16	0.096
				74.50	5.4	1	0.830	90.50	3.1	3.16	0.150
				85.13	5.6	1	0.861	95.00	3.1	3.16	0.150
				93.25	5.7	1	0.876	100.00	4.1	3.16	0.199
				102.00	6.4	1	0.984	104.75	5.2	3.16	0.252
				112.00	6.6	1	1.014	111.00	6.4	3.16	0.311
				124.50	7.0	1	1.076	117.50	8.6	3.16	0.418
				139.50	7.3	1	1.122	122.00	8.9	3.16	0.432
								128.50	3.3	1	0.507
								135.75	4.0	1	0.614
								141.75	4.3	1	0.661

Rossdale WTP Phase II

Test #R15 Date: 16/07/1998 Q= 29.1 L/min Co= 6.3

D= 239 mm Cback= 0.3 31.6

CR6

Inlet				Intercell Outlet				Outlet			
Time (min	C	level	C/Co	Time (min	C	level	C/Co	Time (min	C	level	C/Co
0.85	6.3	1	0.998	8.93	0.4	31.6	0.001	20.63	0.9	31.6	0.003
4.85	6.3	1	0.998	13.77	0.6	31.6	0.002	50.00	0.4	31.6	0.001
48.50	6.2	1	0.983	18.52	0.4	31.6	0.001	59.25	0.6	31.6	0.002
85.25	6.1	1	0.967	25.03	0.4	31.6	0.001	69.50	0.6	31.6	0.002
113.25	6.1	1	0.967	29.22	0.4	31.6	0.001	75.50	0.5	31.6	0.001
132.50	6.0	1	0.951	34.00	2.8	31.6	0.013	83.50	0.6	31.6	0.002
				37.48	1.0	3.16	0.049	89.00	0.7	31.6	0.002
				40.88	0.9	3.16	0.044	92.50	1.4	31.6	0.006
				44.10	1.9	3.16	0.094	96.00	3.2	31.6	0.015
				47.75	3.5	3.16	0.174	98.75	4.1	31.6	0.019
				53.50	5.8	3.16	0.290	101.75	6.6	31.6	0.032
				58.00	7.6	3.16	0.380	105.25	2.1	3.16	0.104
				63.00	4.9	3.16	0.245	109.00	1.8	3.16	0.089
				68.00	8.5	3.16	0.425	111.50	3.3	3.16	0.164
				74.00	3.6	1	0.570	119.75	4.2	3.16	0.209
				78.75	3.5	1	0.554	126.25	5.8	3.16	0.290
				84.50	4.3	1	0.681	130.75	7.5	3.16	0.375
				112.50	5.0	1	0.792	133.75	7.6	3.16	0.380
				131.75	5.3	1	0.840	137.25	8.4	3.16	0.420

Rossdale WTP Phase II

Test #R16 Date: 20/07/1998 Q= 9.7 L/min Co= 6.8

D= 239 mm Cback= 0.4 31.6

CR6

Inlet				Intercell Outlet				Outlet			
Time (min)	C	level	C/Co	Time (min)	C	level	C/Co	Time (min	C	level	C/Co
1.25	6.8	1	0.998	9.25	1.0	31.6	0.003	10.75	0.6	31.6	0.001
3.50	7.0	1	1.028	23.50	0.6	31.6	0.001	22.75	0.7	31.6	0.001
5.50	7.0	1	1.028	36.00	0.6	31.6	0.001	58.50	0.5	31.6	0.000
24.25	6.8	1	0.998	49.00	0.6	31.6	0.001	87.50	0.4	31.6	0.000
59.15	6.5	1	0.954	57.25	0.6	31.6	0.001	115.25	0.5	31.6	0.000
89.15	6.5	1	0.954	62.75	0.5	31.6	0.000	147.75	0.5	31.6	0.000
116.50	6.5	1	0.954	67.00	0.5	31.6	0.000	169.00	0.6	31.6	0.001
149.25	6.4	1	0.939	70.50	0.4	31.6	0.000	183.50	0.7	31.6	0.001
184.50	6.4	1	0.939	75.25	0.4	31.6	0.000	191.50	0.9	31.6	0.002
247.00	6.4	1	0.939	79.25	7.3	31.6	0.032	201.50	1.8	31.6	0.007
305.00	6.3	1	0.925	82.25	5.1	31.6	0.022	206.25	1.4	31.6	0.005
318.50	6.3	1	0.925	85.25	1.1	3.16	0.049	211.75	2.6	31.6	0.010
				88.50	3.0	3.16	0.138	215.50	3.5	31.6	0.014
				92.00	4.9	3.16	0.226	221.50	5.7	31.6	0.025
				94.75	5.4	3.16	0.249	232.00	9.0	31.6	0.040
				98.75	3.9	3.16	0.180	240.00	0.9	3.16	0.040
				102.25	2.7	3.16	0.124	244.75	0.9	3.16	0.040
				104.00	3.9	3.16	0.180	249.50	1.6	3.16	0.073
				108.25	3.8	3.16	0.175	254.00	1.7	3.16	0.077
				113.75	6.0	3.16	0.277	260.00	1.8	3.16	0.082
				120.75	3.7	3.16	0.170	268.00	2.3	3.16	0.105
				125.75	5.1	3.16	0.235	272.75	2.8	3.16	0.128
				136.25	6.0	3.16	0.277	277.50	3.3	3.16	0.152
				146.25	6.7	3.16	0.310	283.75	3.7	3.16	0.170
				154.75	7.2	3.16	0.333	291.00	3.7	3.16	0.170
				167.50	3.3	1	0.483	302.75	4.2	3.16	0.194
				181.75	2.8	1	0.410	319.75	4.9	3.16	0.226
				202.25	3.8	1	0.557				
				233.00	4.5	1	0.660				
				255.00	4.1	1	0.601				
				270.75	5.0	1	0.733				
				304.00	5.2	1	0.763				
				320.50	5.1	1	0.748				

Rossdale WTP Phase II

Test #R17 Date: 22/07/1998 Q= 48.5 L/min Co= 8.4

D= 239 mm Cback= 0.4 31.6

CR6

Inlet				Intercell Outlet				Outlet			
Time (min)	C	level	C/Co	Time (min)	C	level	C/Co	Time (min)	C	level	C/Co
1.00	8.4	1	0.998	5.25	0.8	31.6	0.002	6.25	1.4	31.6	0.004
2.00	8.4	1	0.998	10.25	0.6	31.6	0.001	15.00	1.1	31.6	0.003
4.00	8.4	1	0.998	14.25	0.4	31.6	0.000	24.25	0.7	31.6	0.001
16.00	8.3	1	0.987	18.00	1.0	31.6	0.002	37.00	0.5	31.6	0.000
38.50	8.3	1	0.987	21.25	2.2	31.6	0.007	44.75	0.6	31.6	0.001
61.00	8.3	1	0.987	23.00	4.2	31.6	0.014	52.00	0.6	31.6	0.001
74.00	8.2	1	0.975	26.25	5.1	31.6	0.018	59.50	1.1	31.6	0.003
81.25	8.2	1	0.975	29.67	6.0	31.6	0.021	66.00	2.9	31.6	0.009
				33.50	9.2	31.6	0.033	69.50	6.4	31.6	0.023
				35.75	2.6	3.16	0.096	72.50	9.4	31.6	0.034
				37.75	6.2	3.16	0.232	75.00	2.6	3.16	0.096
				40.75	7.7	3.16	0.289	77.25	2.2	3.16	0.081
				45.75	3.2	1	0.379	79.75	4.7	3.16	0.176
				50.75	4.6	1	0.546	82.17	5.3	3.16	0.198
				60.75	6.2	1	0.737				
				73.25	7.2	1	0.856				
				80.42	7.4	1	0.879				

Rossdale WTP Phase II

Test #R18 Date: 24/07/1998 Q= 38.8 L/min Co= 7.6

D= 239 mm Cback= 0.4 31.6

CR6

Inlet				Intercell Outlet				Outlet			
Time (min)	C	level	C/Co	Time (min)	C	level	C/Co	Time (min)	C	level	C/Co
1.08	7.6	1	0.998	8.50	0.9	31.6	0.002	9.50	0.8	31.6	0.002
3.00	7.7	1	1.011	16.42	0.6	31.6	0.001	27.25	0.4	31.6	0.000
5.50	7.5	1	0.985	20.75	0.7	31.6	0.001	39.00	0.4	31.6	0.000
28.00	7.2	1	0.946	26.00	6.6	31.6	0.026	47.25	0.6	31.6	0.001
65.75	7.2	1	0.946	29.00	1.3	3.16	0.052	56.50	0.7	31.6	0.001
95.00	7.2	1	0.946	33.50	1.4	3.16	0.057	64.25	0.6	31.6	0.001
108.00	7.1	1	0.933	38.00	1.9	3.16	0.077	70.00	1.1	31.6	0.003
				40.00	3.2	3.16	0.132	74.25	1.6	31.6	0.005
				46.50	9.0	3.16	0.373	79.00	3.5	31.6	0.013
				52.50	4.6	1	0.604	86.75	9.1	31.6	0.036
				65.00	6.1	1	0.801	89.50	1.1	3.16	0.044
				94.25	6.8	1	0.893	93.50	1.9	3.16	0.077
				107.25	7.0	1	0.919	100.50	3.0	3.16	0.123
								103.50	4.4	3.16	0.182
								106.50	5.5	3.16	0.227
								109.00	6.6	3.16	0.273

Rossdale WTP Phase II

Test #R19 Date: 31/07/1998 Q= 29.1 L/min Co= 6.7

D= 239 mm Cback= 0.4 31.6

CR7

Inlet				Intercell Outlet				Outlet			
Time (min)	C	level	C/Co	Time (min)	C	level	C/Co	Time (min)	C	level	C/Co
1.00	6.7	1	0.998	11.75	0.9	31.6	0.002	12.50	0.8	31.6	0.002
3.00	6.8	1	1.013	20.00	0.5	31.6	0.000	18.00	0.7	31.6	0.001
10.25	6.8	1	1.013	29.00	0.5	31.6	0.000	36.25	0.6	31.6	0.001
29.75	6.4	1	0.953	35.00	0.8	31.6	0.002	49.50	0.4	31.6	0.000
60.75	6.5	1	0.968	38.00	1.6	31.6	0.006	66.25	0.4	31.6	0.000
96.00	6.5	1	0.968	40.75	6.2	31.6	0.027	85.00	0.8	31.6	0.002
119.25	6.4	1	0.953	43.00	6.0	31.6	0.026	94.50	1.2	31.6	0.004
138.25	6.4	1	0.953	45.50	1.0	3.16	0.045	104.00	4.2	31.6	0.018
				48.25	1.8	3.16	0.083	109.00	1.1	3.16	0.050
				50.50	2.0	3.16	0.093	113.00	1.6	3.16	0.074
				54.00	3.0	3.16	0.140	116.25	1.6	3.16	0.074
				59.00	4.9	3.16	0.230	120.00	2.8	3.16	0.130
				65.00	7.1	3.16	0.333	123.75	3.5	3.16	0.163
				69.25	8.6	3.16	0.404	126.00	3.4	3.16	0.159
				76.50	3.6	1	0.535	131.75	3.8	3.16	0.178
				83.00	4.6	1	0.685	136.00	6.4	3.16	0.300
				95.25	5.3	1	0.789	139.50	7.6	3.16	0.357
				105.00	5.8	1	0.864				
				118.50	6.0	1	0.894				
				137.50	6.2	1	0.923				

Rossdale WTP Phase II

Test #R20 Date: 04/08/1998 Q= 58.2 L/min Co= 7.4

D= 239 mm Cback= 0.4 31.6

CR7

Inlet				Intercell Outlet				Outlet			
Time (min)	C	level	C/Co	Time (min)	C	level	C/Co	Time (min)	C	level	C/Co
0.75	7.4	1	0.998	7.00	0.9	31.6	0.002	8.00	1.0	31.6	0.003
1.50	7.5	1	1.012	17.50	2.1	31.6	0.007	22.50	0.6	31.6	0.001
3.50	7.5	1	1.012	21.00	7.1	31.6	0.029	39.00	0.7	31.6	0.001
18.25	7.0	1	0.944	23.50	1.1	3.16	0.045	48.00	1.0	31.6	0.003
35.00	7.1	1	0.958	25.75	1.8	3.16	0.075	53.50	3.4	31.6	0.013
56.75	7.1	1	0.958	29.00	4.1	3.16	0.174	58.25	1.0	3.16	0.041
67.00	6.9	1	0.931	33.50	6.8	3.16	0.289	61.50	2.0	3.16	0.084
				40.00	3.8	1	0.512	63.50	2.9	3.16	0.122
				45.50	5.5	1	0.742	65.50	3.5	3.16	0.148
				55.50	6.2	1	0.836	68.25	3.3	3.16	0.139
				66.25	6.6	1	0.890				

Rossdale WTP Phase II

Test #R21 Date: 05/08/1998 Q= 29.1 L/min Co= 6.8

D= 239 mm Cback= 0.4 31.6

CR7

Inlet				Intercell Outlet				Outlet			
Time (min)	C	level	C/Co	Time (min)	C	level	C/Co	Time (min)	C	level	C/Co
1.50	6.8	1	0.998	7.75	0.7	31.6	0.001	9.00	0.7	31.6	0.001
2.75	7.0	1	1.028	22.50	0.9	31.6	0.002	23.75	0.6	31.6	0.001
14.25	6.9	1	1.013	30.00	0.5	31.6	0.000	56.00	0.4	31.6	0.000
20.75	6.8	1	0.998	35.50	3.2	31.6	0.013	69.50	0.7	31.6	0.001
61.00	6.5	1	0.954	37.50	3.5	31.6	0.014	81.00	0.7	31.6	0.001
103.25	6.6	1	0.969	43.50	8.0	31.6	0.035	90.00	0.9	31.6	0.002
133.00	6.5	1	0.954	46.75	1.2	3.16	0.054	101.50	2.8	31.6	0.011
				49.00	1.3	3.16	0.059	105.00	4.4	31.6	0.019
				51.75	1.8	3.16	0.082	110.00	9.4	31.6	0.042
				53.75	2.2	3.16	0.101	115.00	1.2	3.16	0.054
				56.75	2.0	3.16	0.091	117.00	2.0	3.16	0.091
				60.00	3.6	3.16	0.166	120.00	2.3	3.16	0.105
				70.50	9.1	3.16	0.422	125.00	3.3	3.16	0.152
				79.50	4.0	1	0.586	130.00	4.6	3.16	0.212
				102.50	5.8	1	0.851	134.50	5.2	3.16	0.240
				132.00	6.4	1	0.939				

Rossdale WTP Phase II

Test #R22 Date: 06/08/1998 Q= 38.8 L/min Co= 6.6

D= 239 mm Cback= 0.4 31.6

CR7

Inlet				Intercell Outlet				Outlet			
Time (min)	C	level	C/Co	Time (min)	C	level	C/Co	Time (min)	C	level	C/Co
1.75	6.6	1	0.998	5.25	0.8	31.6	0.002	6.75	1	31.6	0.003
3.5	6.7	1	1.013	15.5	0.8	31.6	0.002	31.5	0.7	31.6	0.001
9.75	6.6	1	0.998	22.25	0.8	31.6	0.002	62.25	0.9	31.6	0.002
30	6.3	1	0.953	26	2.5	31.6	0.010	70.25	0.8	31.6	0.002
60.75	6.4	1	0.968	34.5	6.2	31.6	0.028	75	1	31.6	0.003
92	6.2	1	0.937	39.25	1.2	3.16	0.056	80	4.1	31.6	0.018
				44.5	3	3.16	0.142	85	5.4	31.6	0.024
				50.25	4.4	3.16	0.209	90	1.1	3.16	0.051
				60	5.8	3.16	0.276	94.75	2.1	3.16	0.099
				75.75	3.7	1	0.559	98.75	2.9	3.16	0.137
				91	5.5	1	0.831	100.75	3.3	3.16	0.156

Rossdale WTP Phase II

Test #R23 Date: 28/08/1998 Q= 29.1 L/min Co= 5.6

D= 239 mm Cback= 0.3 31.6

CR8

Inlet				Intercell Outlet				Outlet			
Time (min)	C	level	C/Co	Time (min)	C	level	C/Co	Time (min)	C	level	C/Co
0.75	5.6	1	0.998	14.75	0.8	31.6	0.003	15.50	0.7	31.6	0.002
2.75	5.7	1	1.016	31.75	1.4	31.6	0.006	33.25	0.4	31.6	0.001
8.25	5.6	1	0.998	36.75	2.9	31.6	0.015	48.75	0.5	31.6	0.001
16.75	5.6	1	0.998	42.00	6.0	31.6	0.032	60.75	0.3	31.6	0.000
47.50	5.5	1	0.980	46.00	8.9	31.6	0.049	78.75	0.4	31.6	0.001
105.00	5.4	1	0.963	51.75	1.2	3.16	0.066	95.75	1.1	31.6	0.005
131.75	5.3	1	0.945	55.00	1.8	3.16	0.100	103.00	2.7	31.6	0.014
				59.00	2.8	3.16	0.157	106.50	3.3	31.6	0.017
				64.50	4.0	3.16	0.224	110.00	4.7	31.6	0.025
				71.75	6.9	3.16	0.388	114.75	9.1	31.6	0.050
				77.25	9.4	3.16	0.529	118.00	1.8	3.16	0.100
				91.00	3.9	1	0.695	121.50	1.7	3.16	0.094
				116.50	4.9	1	0.873	126.25	2.7	3.16	0.151
				130.75	5.1	1	0.909	130.00	3.3	3.16	0.185
								133.00	3.7	3.16	0.207
								139.75	4.6	3.16	0.258

Rossdale WTP Phase II

Test #R24 Date: 01/06/1999 Q= 41.7 L/min Co= 185

D= 239 mm Cback= 0.96

CR9

Inlet			Intercell Outlet			East Cell Only
Time (min)	C	C/Co	Time (min	C	C/Co	
0.70	185	0.995	2.08	1.61	0.004	
1.25	195	1.049	3.00	1.34	0.002	
3.50	195	1.049	5.00	1.54	0.003	
20.50	197	1.060	7.25	1.20	0.001	
28.00	197	1.060	9.00	1.04	0.000	
41.75	196	1.054	10.00	0.96	0.000	
			11.25	1.54	0.003	
			12.00	1.50	0.003	
			13.00	2.05	0.006	
			14.00	1.80	0.005	
			15.00	3.63	0.014	
			16.50	8.77	0.042	
			17.75	12.10	0.060	
			19.25	15.60	0.079	
			21.50	26.30	0.137	
			23.25	35.00	0.184	
			25.25	39.90	0.210	
			27.25	45.30	0.240	
			30.25	54.60	0.290	
			34.00	70.70	0.377	
			38.25	77.50	0.414	
			41.00	91.00	0.487	
			44.50	95.60	0.512	

Rossdale WTP Phase II

Test #R25 Date: 02/06/1999 Q= 58.2 L/min Co= 194

D= 239 mm Cback= 3.5

CR9

Inlet			Intercell Outlet			East Cell Only
Time (min)	C	C/Co	Time (min	C	C/Co	
0.75	194	0.982	2.50	5.34	0.009	
1.75	199	1.008	3.50	5.01	0.008	
20.00	202	1.023	5.00	3.96	0.002	
29.50	199	1.008	6.00	3.8	0.002	
37.75	197	0.997	7.00	3.99	0.003	
			8.00	3.5	0.000	
			9.00	4.32	0.004	
			10.00	8.56	0.026	
			11.00	10.8	0.038	
			12.00	14.8	0.058	
			13.00	14.9	0.059	
			14.00	16.7	0.068	
			15.00	20.6	0.088	
			16.25	21	0.090	
			17.25	26.1	0.116	
			18.25	31.7	0.145	
			19.50	35.6	0.165	
			21.25	46	0.219	
			23.50	52.7	0.254	
			25.50	64.4	0.314	
			28.75	81.3	0.401	
			33.00	92.1	0.457	
			37.00	109	0.544	

Rossdale WTP Phase II

Test #R2(Date: 10/06/1999 Q= 58.2 L/min Co= 214

D= 239 mm Cback= 0.84

CR10

Inlet			South Intercell Outlet			North Intercell Outlet			Outlet		
Time (min)	C	C/Co	Time (min	C	C/Co	Time (min	C	C/Co	Time (min	C	C/Co
0.67	214	0.996	2.75	2.08	0.006	3.33	1.32	0.002	3.92	2.72	0.009
1.33	245	1.141	5.75	1.21	0.002	9.33	0.95	0.001	26.08	1.8	0.004
4.50	244	1.136	6.83	1.38	0.003	10.42	0.92	0.000	28.00	1.13	0.001
25.17	244	1.136	7.83	1.32	0.002	11.50	0.84	0.000	30.75	1.31	0.002
54.00	248	1.155	8.75	1.34	0.002	12.58	1.01	0.001	33.42	2.62	0.008
60.17	246	1.146	9.92	1.16	0.001	13.75	1	0.001	35.00	2.95	0.010
			11.00	0.84	0.000	15.00	2.73	0.009	37.25	5.25	0.021
			12.00	1.16	0.001	16.92	12.8	0.056	38.92	6.94	0.029
			13.25	2.46	0.008	18.25	23.2	0.104	41.00	8.53	0.036
			14.42	8.93	0.038	19.92	26.5	0.120	42.33	10.2	0.044
			16.00	15.8	0.070	21.42	33.5	0.153	43.50	12.3	0.054
			17.58	15.6	0.069	23.00	44.5	0.204	44.58	13.4	0.059
			18.83	17.4	0.077	24.50	59.6	0.275	46.00	17	0.076
			20.75	23.3	0.105	27.08	78.6	0.363	47.50	19.5	0.087
			22.33	27.6	0.125	32.33	125	0.580	48.58	23.8	0.107
			24.00	38.4	0.176	40.33	159	0.739	50.08	24.6	0.111
			26.58	57.5	0.265	52.92	193	0.898	51.50	29.8	0.135
			31.75	97.8	0.453	59.17	211	0.982	52.50	32.2	0.147
			39.92	142	0.660				54.92	44	0.202
			53.50	190	0.884				56.75	48.5	0.223
			59.67	204	0.949				58.25	53.8	0.247
									61.00	60.4	0.278

Rossdale WTP Phase II

Test #R2' Date: 16/06/1999 Q= 58.2 L/min Co= 200

D= 239 mm Cback= 0.768

CR11

Inlet			South Intercell Outlet			North Intercell Outlet			Outlet		
Time (min)	C	C/Co	Time (min	C	C/Co	Time (min	C	C/Co	Time (min	C	C/Co
1.25	200	0.996	2.75	2.13	0.007	3.25	1.46	0.003	3.75	1.48	0.004
2.00	202	1.006	4.75	1.17	0.002	5.42	1.17	0.002	6.25	0.87	0.001
7.00	203	1.011	8.00	1.08	0.002	8.50	1.14	0.002	11.17	0.8	0.000
28.00	205	1.021	10.17	1.27	0.003	10.75	0.86	0.000	29.17	1.25	0.002
59.83	206	1.026	12.00	0.86	0.000	12.53	0.77	0.000	31.25	0.92	0.001
67.75	207	1.031	14.25	1.04	0.001	14.75	1.11	0.002	33.75	1.22	0.002
			16.42	0.99	0.001	16.83	2.24	0.007	36.00	1.21	0.002
			18.25	1.28	0.003	18.67	7.15	0.032	38.50	3.42	0.013
			19.80	2.88	0.011	20.25	21.1	0.102	40.25	4.94	0.021
			20.83	6.02	0.026	21.50	36.8	0.180	42.25	6.86	0.030
			22.08	17.4	0.083	22.75	56.5	0.279	44.25	8.33	0.038
			23.50	33.4	0.163	24.00	74.2	0.367	46.50	12.6	0.059
			25.25	48.7	0.240	25.75	87.5	0.434	48.25	14.9	0.071
			27.00	59	0.291	27.50	108	0.536	49.25	19	0.091
			34.25	107	0.531	35.00	131	0.651	50.50	20.6	0.099
			58.67	161	0.801	59.25	177	0.881	51.50	23.3	0.113
			66.75	168	0.836	67.25	186	0.926	52.67	28.7	0.140
									54.33	32.9	0.161
									56.50	39.2	0.192
									58.00	42.8	0.210
									60.50	50.3	0.248
									63.83	64.2	0.317
									66.17	68.1	0.337

Rossdale WTP Phase II

Test #R2 Date: 17/06/1999 Q= 58.2 L/min Co= 220

D= 239 mm Cback= 0.748

CR11

Inlet			South Intercell Outlet			North Intercell Outlet			Outlet		
Time (min)	C	C/Co	Time (min	C	C/Co	Time (min	C	C/Co	Time (min	C	C/Co
0.67	220	0.997	2.08	1.71	0.004	2.50	1.26	0.002	3.00	2.61	0.008
1.25	225	1.019	4.75	1.03	0.001	5.17	1.23	0.002	8.75	0.98	0.001
23.50	216	0.978	8.00	0.9	0.001	8.33	0.84	0.000	14.17	0.83	0.000
58.33	217	0.983	11.75	0.81	0.000	12.08	0.9	0.001	24.50	1.25	0.002
65.33	218	0.988	14.58	0.75	0.000	15.00	0.77	0.000	27.50	1.7	0.004
			17.25	6.11	0.024	17.67	31.5	0.140	30.75	1.19	0.002
			18.83	23	0.101	19.25	61.4	0.276	34.00	1.63	0.004
			20.00	37.9	0.169	20.50	82.3	0.371	37.50	4.92	0.019
			21.00	49.6	0.222	21.50	95.7	0.432	40.50	7.74	0.032
			22.58	67.5	0.303	23.00	104	0.469	42.75	11.3	0.048
			25.17	77.8	0.350	25.58	112	0.506	45.58	19.2	0.084
			34.50	104	0.469	35.00	121	0.547	46.50	20.1	0.088
			57.50	158	0.715	58.00	176	0.797	47.50	23.4	0.103
			64.25	172	0.778	64.75	186	0.842	48.75	29.5	0.131
									49.75	30.5	0.135
									51.25	34.1	0.152
									52.50	39.4	0.176
									54.50	47.5	0.213
									57.00	48.2	0.216
									63.75	72	0.324

Rossdale WTP Phase II

Test #R2 Date: 21/06/1999 Q= 29.1 L/min Co= 120

D= 239 mm Cback= 0.616

CR11

Inlet			South Intercell Outlet			North Intercell Outlet			Outlet		
Time (min)	C	C/Co	Time (min	C	C/Co	Time (min	C	C/Co	Time (min	C	C/Co
0.67	120	0.995	2.25	1.34	0.006	2.75	1.16	0.005	3.25	1.48	0.007
1.33	133	1.103	6.00	1.01	0.003	6.50	0.85	0.002	13.25	0.76	0.001
44.08	124	1.028	9.50	0.82	0.002	10.00	0.8	0.002	44.75	1.04	0.004
70.75	125	1.037	12.25	0.81	0.002	12.75	0.74	0.001	51.00	0.83	0.002
113.00	125	1.037	15.50	0.73	0.001	16.00	0.71	0.001	60.75	1.05	0.004
			18.08	0.68	0.001	17.75	0.69	0.001	65.50	1.47	0.007
			20.50	0.71	0.001	19.92	0.68	0.001	70.25	2.04	0.012
			22.17	0.64	0.000	21.75	0.65	0.000	75.17	3.24	0.022
			24.00	0.62	0.000	23.50	0.65	0.000	77.50	5.92	0.044
			26.50	0.78	0.001	26.00	0.62	0.000	79.00	5.2	0.038
			28.33	0.8	0.002	27.83	0.77	0.001	82.25	5.74	0.043
			30.50	0.67	0.000	30.00	0.65	0.000	84.50	9.52	0.074
			32.50	1.1	0.004	32.00	2.14	0.013	86.50	9.56	0.075
			34.33	3.44	0.024	34.00	7.06	0.054	90.50	10.3	0.081
			36.00	5.35	0.039	35.50	12.7	0.101	93.00	15.7	0.126
			37.33	8.52	0.066	37.00	20.6	0.167	95.00	16.9	0.136
			38.33	10.1	0.079	38.00	23.6	0.192	101.00	17.9	0.144
			39.33	13.3	0.106	39.00	28.6	0.233	110.00	25.1	0.204
			40.75	16.2	0.130	40.33	33	0.270	116.75	35.7	0.292
			43.50	26.9	0.219	43.17	45.1	0.371			
			51.50	43.1	0.354	52.00	66.2	0.547			
			59.25	57.1	0.471	59.75	77	0.637			
			81.25	78.1	0.646	80.83	89.3	0.739			
			112.00	95.5	0.791	112.50	107	0.887			

Rossdale WTP Phase II

Test #R3(Date: 24/06/1999 Q= 58.2 L/min Co= 259

D= 239 mm Cback= 0.861

CR12

Inlet			South Intercell Outlet			North Intercell Outlet			Outlet		
Time (min)	C	C/Co	Time (min	C	C/Co	Time (min	C	C/Co	Time (min	C	C/Co
1.92	259	0.997				3.25	2.2	0.005	3.75	1.42	0.002
2.50	294	1.132				6.50	1.35	0.002	7.00	1.13	0.001
25.00	284	1.093				9.25	1.09	0.001	25.75	1.85	0.004
67.00	280	1.078				11.25	0.97	0.000	28.75	1.37	0.002
						13.25	0.95	0.000	31.50	1.21	0.001
						14.50	0.88	0.000	35.00	1.4	0.002
						15.75	0.86	0.000	38.50	1.91	0.004
						17.50	4.65	0.015	40.00	2.61	0.007
						18.50	16.6	0.061	41.25	2.97	0.008
						19.75	38.4	0.145	42.50	5.42	0.018
						20.75	42.8	0.162	43.75	10.5	0.037
						21.92	85.1	0.325	45.00	10.8	0.038
						24.00	107	0.410	46.25	16.2	0.059
						35.75	216	0.831	47.25	18.1	0.067
						66.00	227	0.873	48.50	23.9	0.089
									49.75	28.8	0.108
									50.75	29.9	0.112
									52.00	38.4	0.145
									53.25	45.6	0.173
									55.25	52.2	0.198
									62.50	91.8	0.351
									65.25	105	0.402

Rossdale WTP Phase II

Test #R31 Date: 25/06/1999 Q= 29.1 L/min Co= 181

D= 239 mm Cback= 1.61

CR12

Inlet			South Intercell Outlet			North Intercell Outlet			Outlet		
Time (min)	C	C/Co	Time (min	C	C/Co	Time (min	C	C/Co	Time (min	C	C/Co
0.83	181	0.991				2.50	2.71	0.006	3.00	2.64	0.006
1.50	202	1.107				7.75	2.06	0.002	8.25	2.16	0.003
51.75	191	1.046				15.50	1.86	0.001	26.75	1.94	0.002
88.75	186	1.019				26.00	1.81	0.001	52.75	2.04	0.002
129.25	190	1.041				29.25	1.81	0.001	61.00	1.79	0.001
						31.25	1.66	0.000	64.33	1.68	0.000
						33.25	1.61	0.000	70.00	1.65	0.000
						35.25	1.64	0.000	74.00	1.67	0.000
						37.00	1.72	0.001	80.00	1.89	0.002
						38.25	1.89	0.002	86.75	2.38	0.004
						39.50	2.78	0.006	89.75	3.31	0.009
						40.75	3.24	0.009	91.50	3.64	0.011
						41.75	7.14	0.031	94.25	5.46	0.021
						43.00	10.1	0.047	96.50	5.34	0.021
						44.00	10.2	0.047	99.25	8.36	0.037
						45.00	13.3	0.065	101.00	11.0	0.052
						46.00	12.4	0.060	102.50	11.5	0.055
						47.00	18.5	0.093	104.25	14.9	0.073
						48.00	21.6	0.110	105.75	17.4	0.087
						49.25	23.8	0.123	107.25	19.3	0.098
						51.00	24.1	0.124	108.50	17.3	0.087
						55.50	30	0.157	109.50	19.1	0.097
						65.75	41.7	0.221	111.25	16.9	0.084
						88.25	107	0.582	113.25	23.1	0.119
						97.00	148	0.809	115.25	27.8	0.145
						128.50	175	0.958	117.00	23.8	0.123
									119.00	32.3	0.170
									123.50	38.8	0.205
									128.00	51.0	0.273

E.L. Smith WTP Phase I

Test #E1 Date: 24/02/1999 Q= 11.2 L/min Co= 190

D= 89 mm Cback= 0.66

CE1

Inlet			Outlet		
Time (min	C	C/Co	Time (min	C	C/Co
0.58	190	0.997	2.78	0.839	0.001
1.12	195	1.023	3.22	0.701	0.000
2.05	196	1.028	3.78	0.697	0.000
9.58	197	1.033	4.25	0.718	0.000
12.77	198	1.039	4.72	4.96	0.023
			5.13	5.99	0.028
			5.63	11.8	0.059
			6.15	26.2	0.134
			6.7	27.6	0.142
			7.22	32.4	0.167
			7.72	23.2	0.119
			8.32	26.6	0.137
			8.92	34.7	0.179
			10.82	51.1	0.265
			11.67	48.1	0.250

E.L. Smith WTP Phase I

Test #E2 Date: 25/02/1999 Q= 10.3 L/min Co= 238

D= 82 mm Cback= 1.56

CE1

Inlet			Outlet		
Time (min	C	C/Co	Time (min	C	C/Co
0.92	238	0.993	2.5	3.13	0.007
1.5	240	1.002	3.13	2.04	0.002
9.08	242	1.010	3.92	2.37	0.003
13.95	245	1.023	4.58	1.89	0.001
18.83	247	1.031	5.3	2.37	0.003
27.75	244	1.019	5.98	20	0.077
36	250	1.044	6.52	19.3	0.075
51.63	255	1.065	7.12	34.6	0.139
			7.7	33.3	0.133
			8.25	37.6	0.151
			10.75	46.2	0.188
			11.5	64.7	0.265
			13.15	59	0.241
			15.58	72.4	0.298
			17.75	87.3	0.360
			20.15	85.2	0.351
			22.13	104	0.430
			24.72	119	0.493
			27	116	0.481
			32.05	138	0.573
			35.33	150	0.624
			40	151	0.628
			45.1	178	0.741
			51.07	186	0.775
			63.5	209	0.872

E.L. Smith WTP Phase I

Test #E3 Date: 03/03/1999 Q= 8.1 L/min Co= 168

D= 86 mm Cback= 0.936

CE1

Inlet			Outlet		
Time (min	C	C/Co	Time (min	C	C/Co
0.37	168	0.994	2.37	1.25	0.002
1.23	188	1.113	2.92	1.03	0.001
4.42	186	1.102	3.67	0.936	0.000
15.55	185	1.096	5.5	1.04	0.001
25.62	189	1.119	6.12	1.29	0.002
43.67	183	1.084	7.2	7.18	0.037
53.83	184	1.090	8	17.9	0.101
			9	23.4	0.134
			10	26.8	0.154
			11.83	31.6	0.183
			13.27	45.2	0.263
			14.63	46.8	0.273
			16.92	60.8	0.356
			18.75	62.2	0.365
			21.25	66.7	0.391
			24.08	64.3	0.377
			27	76.8	0.452
			30.55	79.7	0.469
			35.33	87.2	0.513
			42.67	115	0.679
			53.03	135	0.798

E.L. Smith WTP Phase I

Test #E4 Date: 05/03/1999 Q= 8.1 L/min Co= 501

D= 86 mm Cback= 1.03

CE1

Inlet			Outlet		
Time (min	C	C/Co	Time (min	C	C/Co
0.7	501	0.998	2.83	2.41	0.003
1.5	512	1.020	3.52	1.56	0.001
15.92	516	1.028	4.68	1.1	0.000
21.17	505	1.006	5.58	1.11	0.000
34.5	507	1.010	6.52	2.37	0.003
39.42	515	1.026	7.75	16.3	0.030
45.5	514	1.024	8.95	49.5	0.097
			10	74.3	0.146
			11.17	78.7	0.155
			12.5	74.1	0.146
			13.4	126	0.249
			14.55	140	0.277
			17.83	160	0.317
			20	218	0.433
			22.58	200	0.397
			26.13	236	0.469
			29.58	241	0.479
			33.5	268	0.533
			38.5	316	0.629
			42.25	337	0.671
			44.8	363	0.722
			49	386	0.768

E.L. Smith WTP Phase I

Test #E5 Date: 10/03/1999 Q= 10.3 L/min Co= 159

D= 82 mm Cback= 0.935

CE1

Inlet			Outlet		
Time (min	C	C/Co	Time (min	C	C/Co
1.07	159	0.994	2.67	1.88	0.006
1.67	183	1.145	3.17	1.27	0.002
11.08	183	1.145	3.75	0.935	0.000
16	187	1.170	4.6	1.99	0.002
32.78	185	1.158	5.25	2	0.007
			6.08	18.9	0.113
			6.92	23.3	0.141
			7.42	28	0.170
			8.42	27.7	0.168
			9.08	34.8	0.213
			10.17	41.7	0.256
			13	53.8	0.332
			15.3	64.4	0.399
			17.57	71.8	0.446
			22.05	86.8	0.540
			27.42	108	0.673
			31.87	120	0.749

E.L. Smith WTP Phase II

Test #E6 Date: 17/03/1999 Q= 10.3 L/min Co= 237

D= 82 mm Cback= 0.44

CE2

Inlet			Outlet		
Time (min	C	C/Co	Time (min	C	C/Co
0.5	237	0.998	2.25	0.777	0.001
1.25	264	1.112	3.25	0.664	0.001
11.53	267	1.125	4.5	0.765	0.001
31.5	258	1.087	5.5	0.672	0.001
43.83	256	1.078	6.75	0.579	0.001
69.58	265	1.116	7.5	0.596	0.001
80	269	1.133	9	0.472	0.000
			10.75	0.592	0.001
			12,5	0.751	0.001
			14	0.526	0.000
			16.25	0.61	0.001
			18.25	0.669	0.001
			19.75	2.3	0.008
			21.75	11.5	0.047
			23.5	17.5	0.072
			24.25	22.8	0.094
			24.75	26.1	0.108
			25.5	30.8	0.128
			26.5	39.6	0.165
			27.78	46.4	0.194
			29	58.3	0.244
			30.5	73.9	0.310
			32.5	101	0.424
			37	154	0.648
			43	194	0.817
			52	230	0.969
			60.75	243	1.023
			68.5	255	1.074
			76.17	261	1.099
			79.42	261	1.099

E.L. Smith WTP Phase II

Test #E7 Date: 19/03/1999 Q= 10.3 L/min Co= 452

D= 82 mm Cback= 0.531

CE2

Inlet			Outlet		
Time (min	C	C/Co	Time (min	C	C/Co
1.3	452	0.999	3.17	2.04	0.003
2.33	450	0.994	4.42	1.61	0.002
29.75	460	1.017	5.5	1.4	0.002
44.75	461	1.019	7.3	1.49	0.002
57.5	457	1.010	9.25	1.22	0.002
			12	1.16	0.001
			15	1.22	0.002
			17	5.1	0.010
			18.5	11.6	0.024
			19.5	13.7	0.029
			20.27	20.8	0.045
			21.25	28.9	0.063
			22.5	38.8	0.085
			23.8	56.5	0.124
			24.75	79	0.174
			25.75	85.4	0.188
			27	107	0.236
			29	163	0.359
			32.25	256	0.565
			36	298	0.658
			39.75	343	0.758
			43.5	380	0.840
			51	419	0.926
			57	434	0.959

E.L. Smith WTP Phase II

Test #E8 Date: 22/03/1999 Q= 8.1 L/min Co= 437

D= 86 mm Cback= 0.735

CE2

Inlet			Outlet		
Time (min	C	C/Co	Time (min	C	C/Co
2.62	437	0.998	3.78	2.17	0.003
4.5	439	1.003	5.5	2.34	0.004
34.25	443	1.012	8	2.69	0.004
45	449	1.026	10.5	1.52	0.002
63.25	451	1.030	12.5	1.74	0.002
			15	1.58	0.002
			17.25	2.43	0.004
			19.28	1.98	0.003
			21.5	1.44	0.002
			23.17	2.94	0.005
			25	7	0.014
			26.55	11.6	0.025
			29.08	19.8	0.044
			31	33	0.074
			33.5	46.7	0.105
			35.5	84	0.191
			37.75	123	0.280
			40	170	0.387
			44.5	251	0.573
			48.5	272	0.621
			55.25	326	0.744
			62.75	377	0.861

E.L. Smith WTP Phase II

Test #E9 Date: 24/03/1999 Q= 8.1 L/min Co= 440

D= 86 mm Cback= 0.626

CE2

Inlet			Outlet		
Time (min	C	C/Co	Time (min	C	C/Co
1.75	440	0.999	5	1.7	0.002
3.75	454	1.030	7	2.49	0.004
21.75	434	0.985	12	2.19	0.004
40.75	445	1.010	15	1.91	0.003
59.5	437	0.992	18	1.62	0.002
91	425	0.964	21	1.6	0.002
			23	1.69	0.002
			25.5	7.22	0.015
			27.5	10.7	0.023
			29.5	31.6	0.070
			31.25	47	0.105
			32.5	60.5	0.136
			34.75	90.8	0.205
			37.75	176	0.399
			43.25	250	0.567
			46.5	284	0.644
			53.25	334	0.758
			59	358	0.812
			68.75	377	0.855
			79.5	396	0.899
			90.5	403	0.914

E.L. Smith WTP Phase II

Test #E1 Date: 07/05/1999 Q= 10.3 L/min Co= 369

D= 82 mm Cback= 1.37

CE3

Inlet			Outlet		
Time (min	C	C/Co	Time (min	C	C/Co
1.75	369	0.996	3.75	1.86	0.001
3	373	1.007	6.75	1.88	0.001
12	370	0.999	11.25	1.44	0.000
37	369	0.996	15.25	1.73	0.001
59	372	1.004	21.5	1.37	0.000
			25.5	6.71	0.014
			30.25	81.8	0.218
			31.5	131	0.351
			33.25	182	0.490
			35	229	0.617
			41.25	329	0.888
			46	353	0.953
			50	357	0.964
			57	363	0.980

E.L. Smith WTP Phase II

Test #E1 Date: 07/05/1999 Q= 10.3 L/min Co= 345

D= 82 mm Cback= 2.12

CE3

Inlet			Outlet		
Time (min	C	C/Co	Time (min	C	C/Co
1.33	345	0.994	4	2.12	0.000
2.5	355	1.023	6	2.54	0.001
9.75	352	1.014	9.08	2.35	0.001
33.75	351	1.011	13.5	3.04	0.003
55.5	347	1.000	15.75	2.55	0.001
			18.75	2.44	0.001
			21	2.2	0.000
			23	2.24	0.000
			25	4.5	0.007
			27	16.7	0.042
			29	37.3	0.102
			31	63.6	0.178
			35	178	0.510
			40	272	0.782
			43.75	311	0.895
			50	330	0.950
			54.75	337	0.971

E.L. Smith WTP Phase II

Test #E1 Date: 10/05/1999 Q= 8.1 L/min Co= 285

D= 86 mm Cback= 1.39

CE3

Inlet			Outlet		
Time (min	C	C/Co	Time (min	C	C/Co
0.66	285	0.995	2.75	2.68	0.005
1.75	314	1.097	5	1.77	0.001
11	314	1.097	9.25	3.92	0.009
45.75	306	1.069	13.25	1.76	0.001
71	303	1.058	15.5	1.56	0.001
			20	1.6	0.001
			25	1.39	0.000
			28	1.93	0.002
			30	1.39	0.000
			32	1.97	0.002
			34.5	7.97	0.023
			36.5	16.8	0.054
			38.5	29.1	0.097
			40.5	56.6	0.194
			45	132	0.458
			50.5	225	0.785
			55	260	0.907
			60.08	283	0.988
			70.5	296	1.034

E.L. Smith WTP Phase II

Test #E1 Date: 11/05/1999 Q= 8.1 L/min Co= 303

D= 86 mm Cback= 1.77

CE3

Inlet			Outlet		
Time (min	C	C/Co	Time (min	C	C/Co
1.25	303	0.994	3	2.87	0.004
2.25	314	1.030	5	2.36	0.002
5.75	318	1.044	10	4.01	0.007
15.5	310	1.017	15	2.22	0.001
53	312	1.024	20	1.82	0.000
69.25	318	1.044	25	1.95	0.001
			30	1.77	0.000
			32	1.9	0.000
			34	3.95	0.007
			36	11.7	0.033
			38	25	0.077
			40	48.2	0.153
			42	70.1	0.226
			47	175	0.572
			52.25	232	0.760
			62	282	0.925
			68.75	296	0.971

Appendix B

Model Tracer Study
F-curves

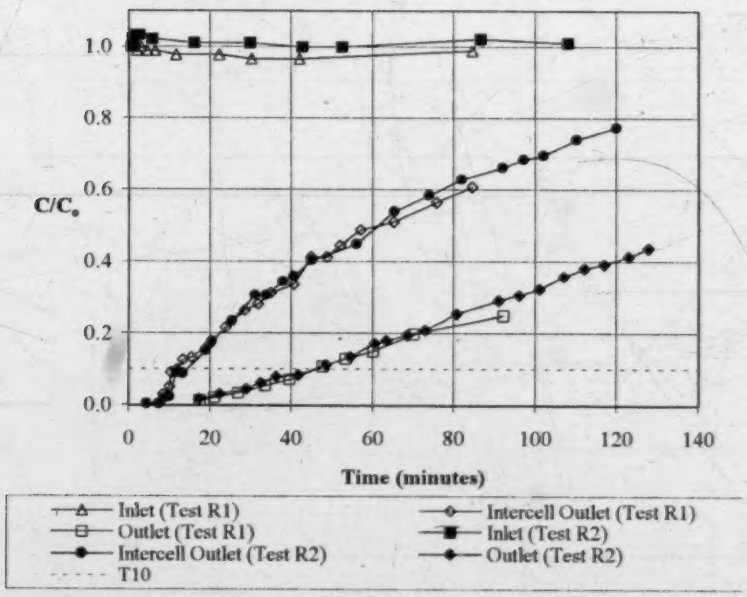

Figure B-1. F-curves for R1 and R2 (CR1 + 29.1 L/min + 273 mm)

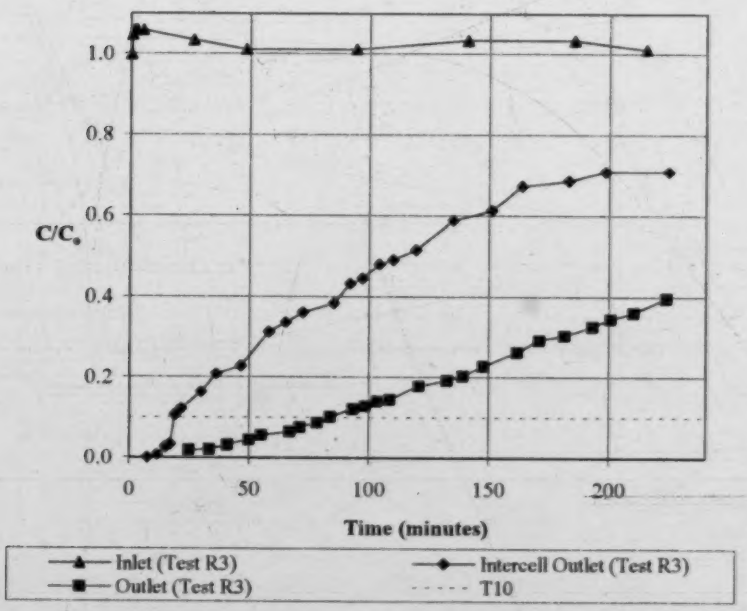

Figure B-2. F-curve for R3 (CR1 + 14.5 L/min + 273 mm)

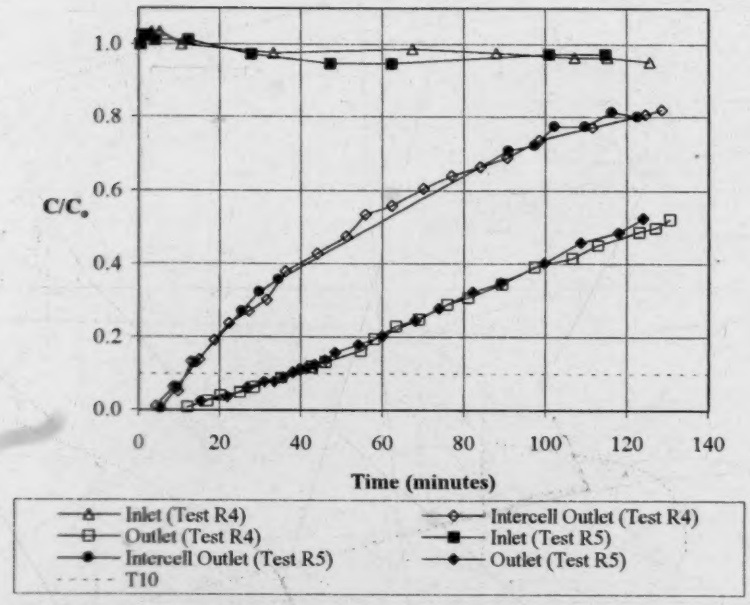

Figure B-3. F-curves for R4 (CR1 + 29.1 L/min + 239 mm) and R5 (CR1 + 29.1 L/min + 220 mm)

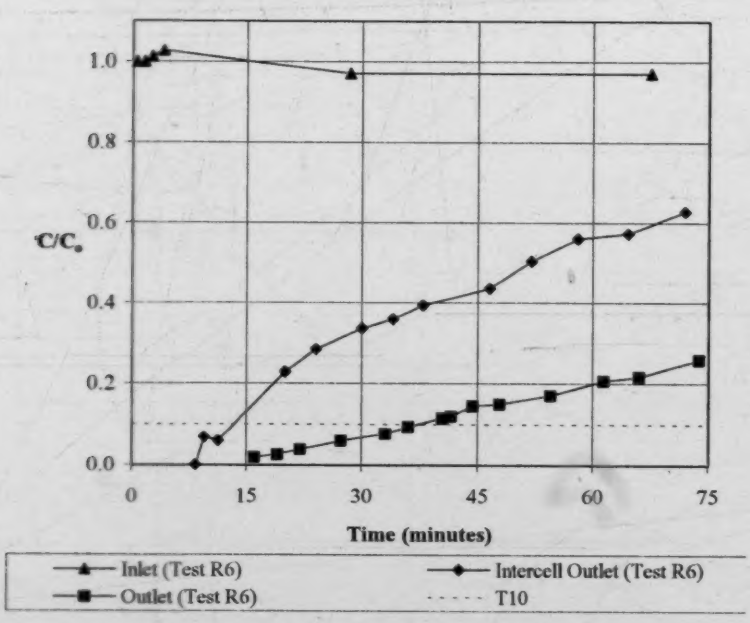

Figure B-4. F-curve for R6 (CR2 + 29.1 L/min + 239 mm)

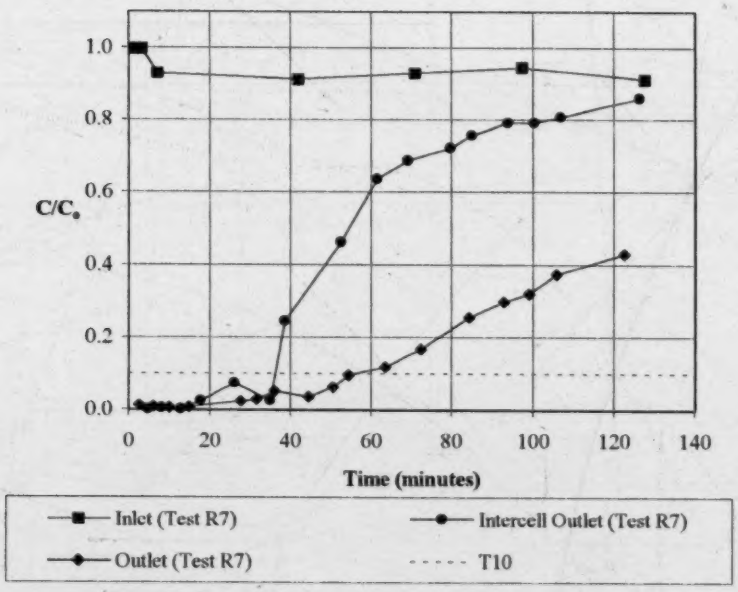

Figure B-5. F-curves for R7 (CR3 + 29.1 L/min + 239 mm)

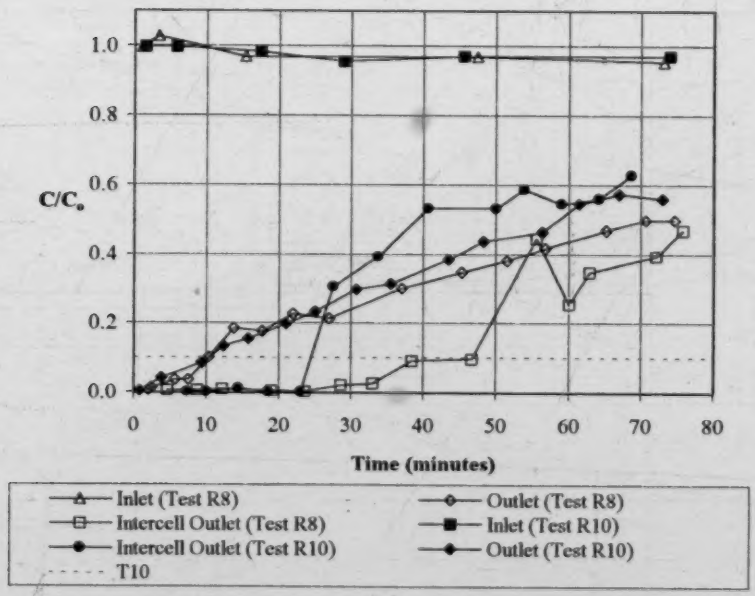

Figure B-6. F-curve for R8 and R10 (CR3 + 58.2 L/min + 239 mm)

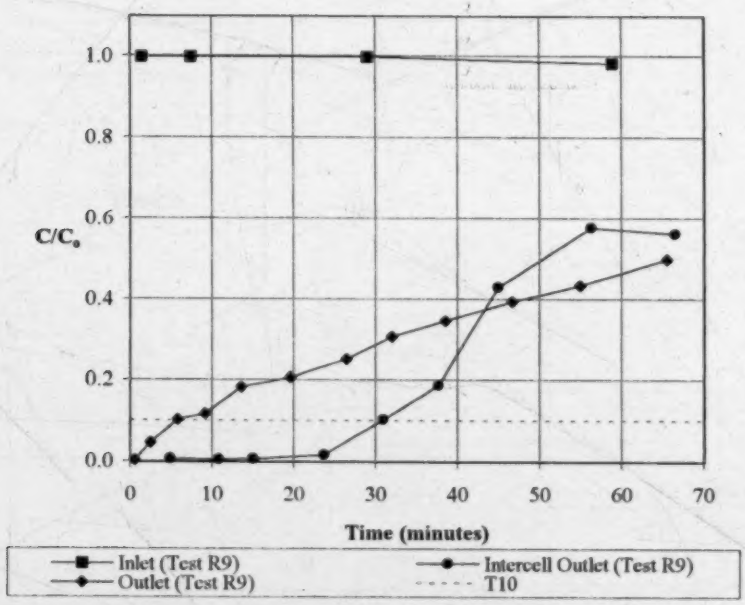

Figure B-7. F-curve for R9 (CR3 + 58.2 L/min + 265 mm)

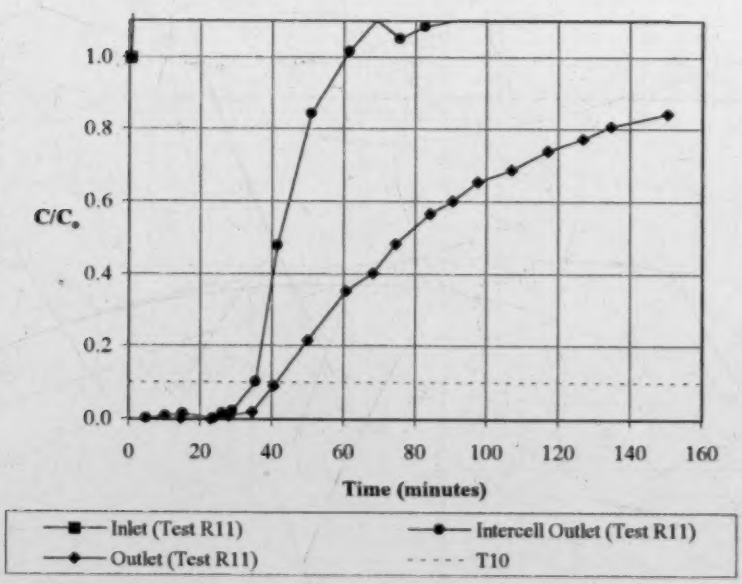

Figure B-8. F-curve for R11 (CR3 + 29.1 L/min +167 mm)

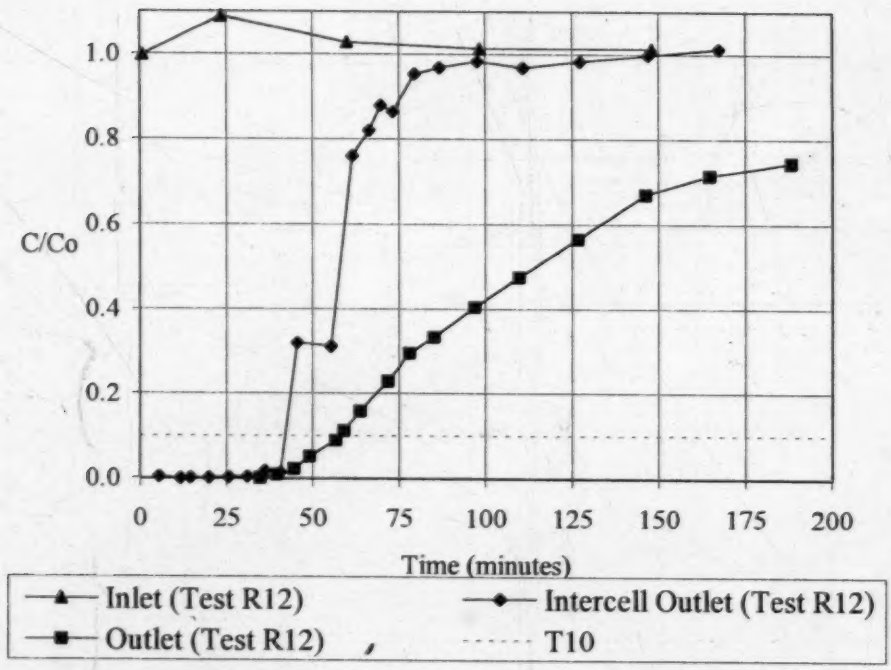

Figure B-9. F-curve for R12 (CR3 + 23.5 L/min + 174 mm)

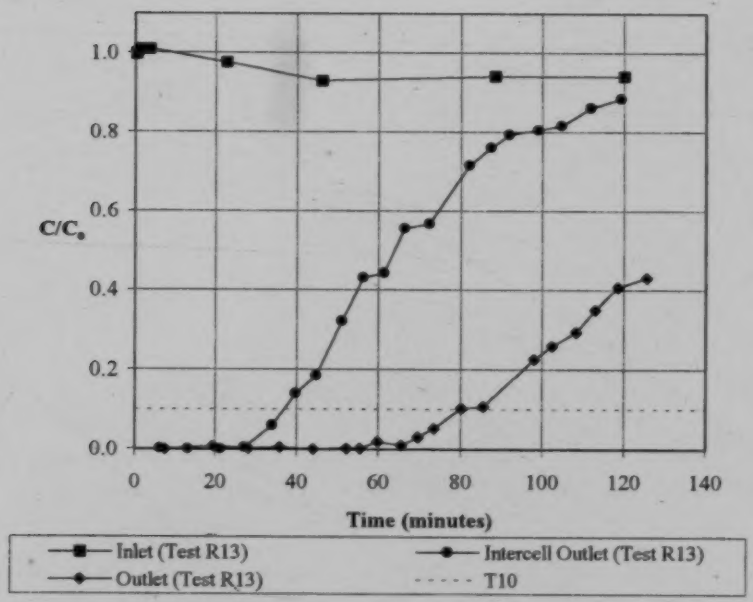

Figure B-10. F-curve for R13 (CR4 + 29.1 L/min + 239 mm)

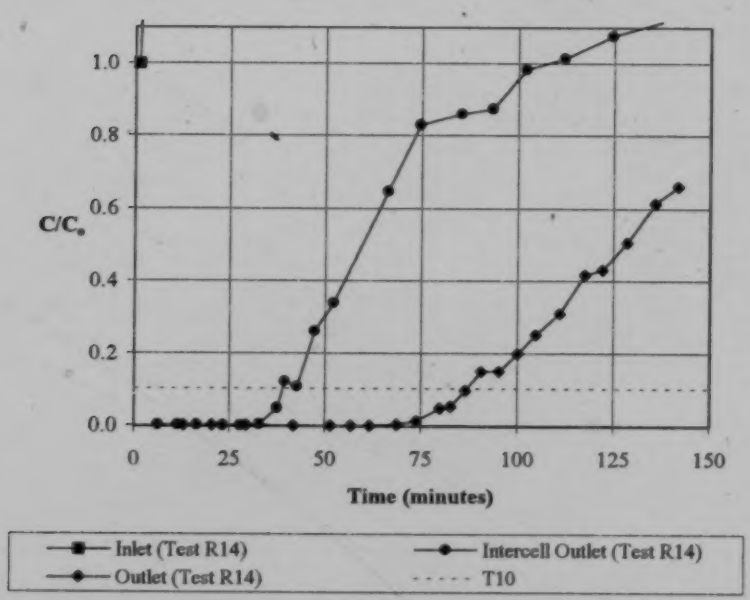

Figure B-11. F-curve for R14 (CR5 + 29.1 L/min + 239 mm)

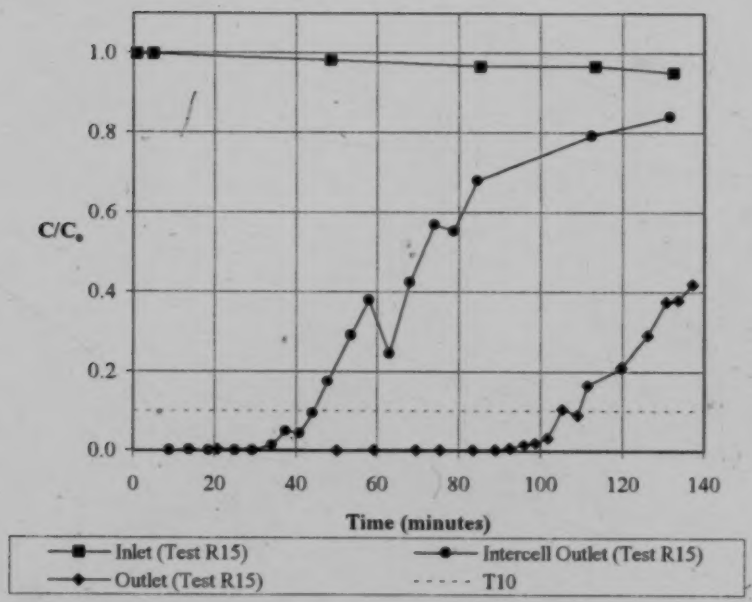

Figure B-12. F-curve for R15 (CR6 + 29.1 L/min + 239 mm)

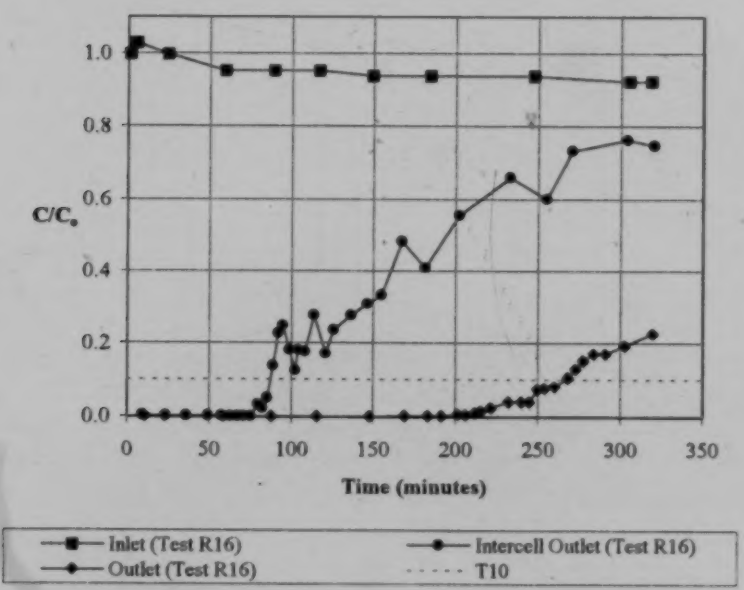

Figure B-13. F-curve for R16 (CR6 + 9.7 L/min + 239 mm)

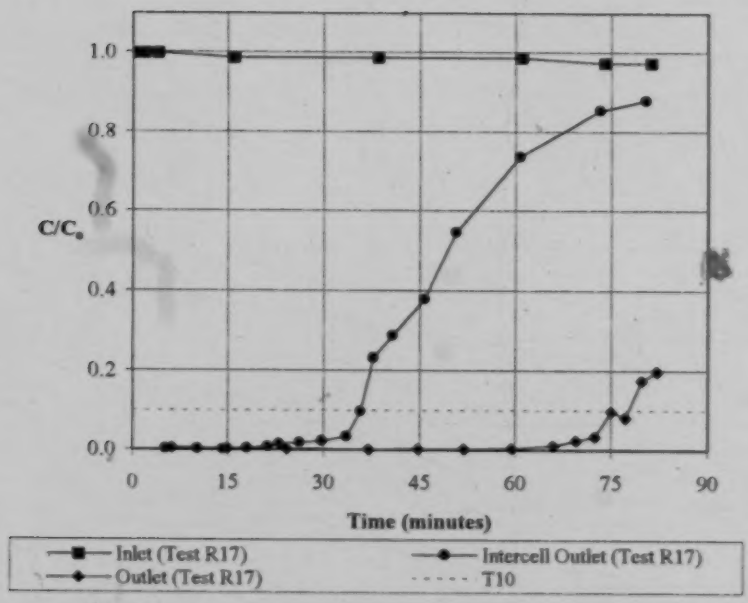

Figure B-14. F-curve for R17 (CR6 + 48.5 L/min + 239 mm)

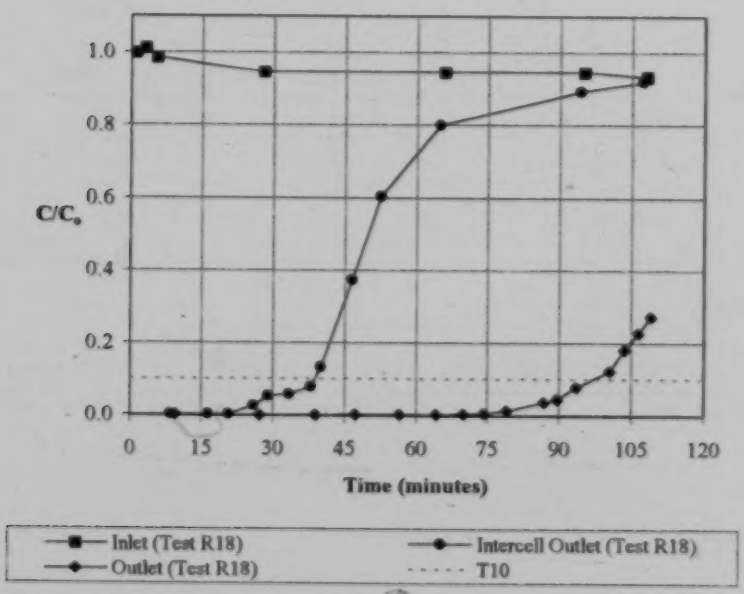

Figure B-15. F-curve for R18 (CR6 + 38.8 L/min + 239 mm)

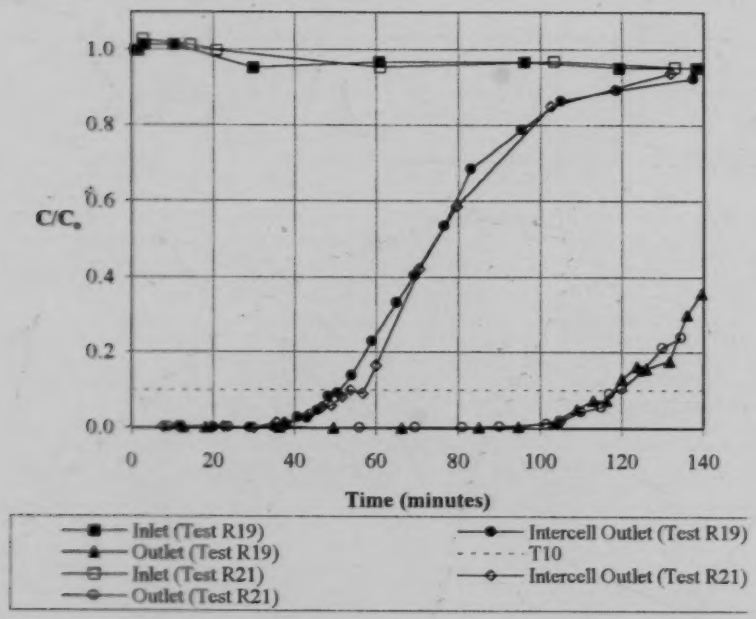

Figure B-16. F-curves for R19 and R21 (CR7 + 29.1 L/min + 239 mm)

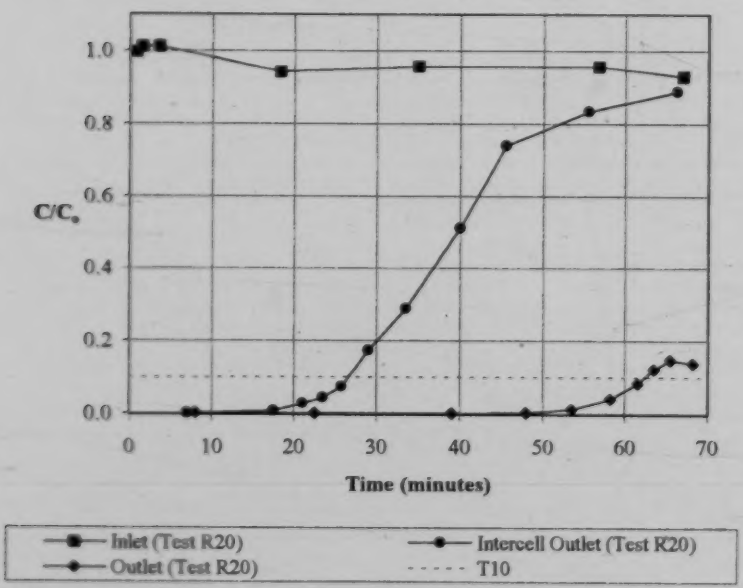

Figure B-17. F-curve for R20 (CR7 + 58.2 L/min + 239 mm)

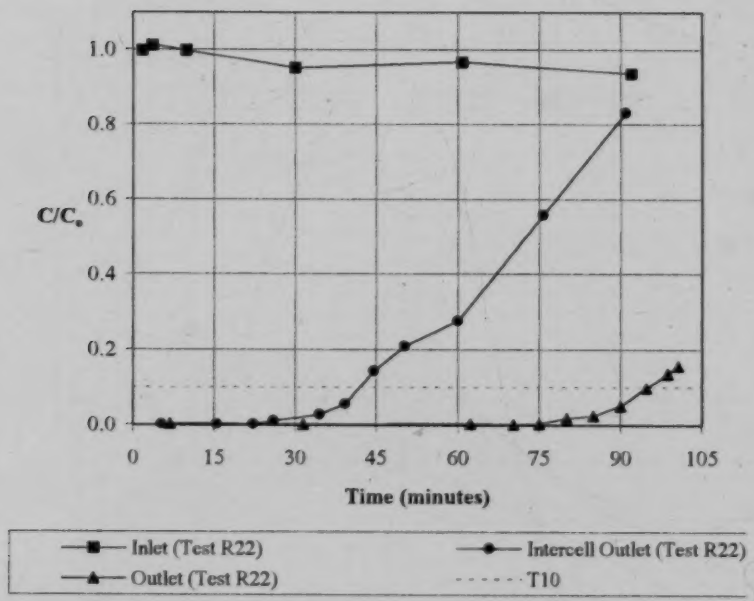

Figure B-18. F-curve for R22 (CR7 + 38.8 L/min + 239 mm)

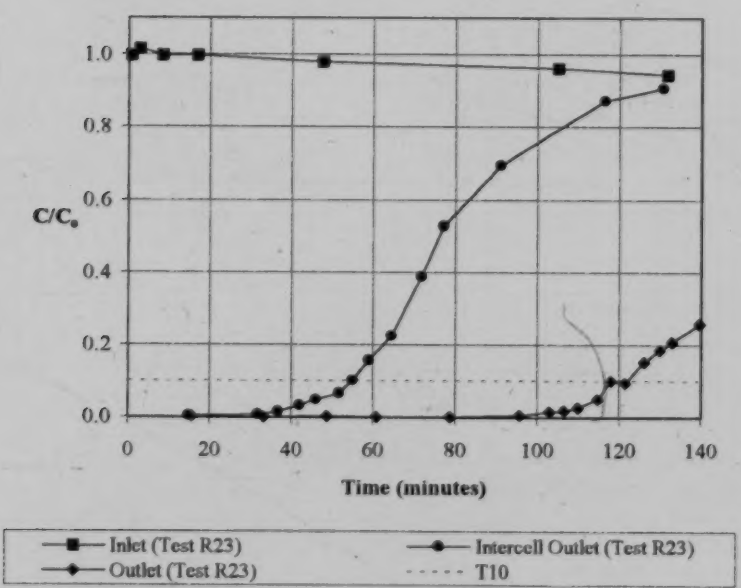

Figure B-19. F-curve for R23 (CR8 + 29.1 L/min + 239 mm)

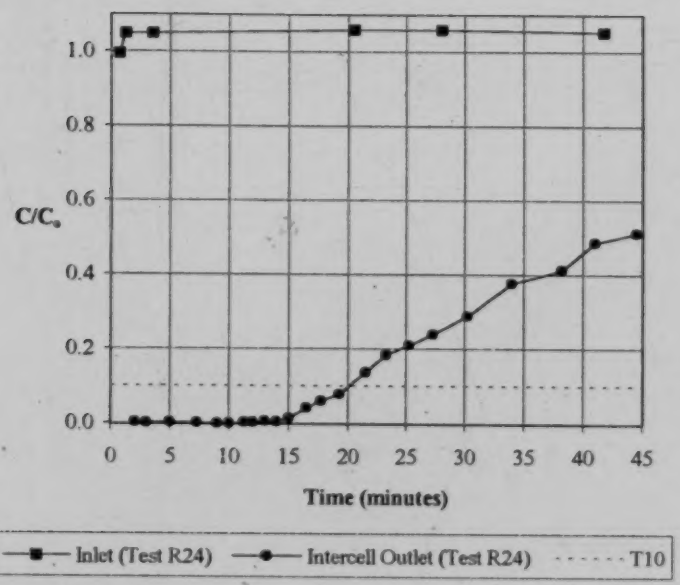

Figure B-20. F-curve for R24 (CR9 + 41.7 L/min + 239 mm)

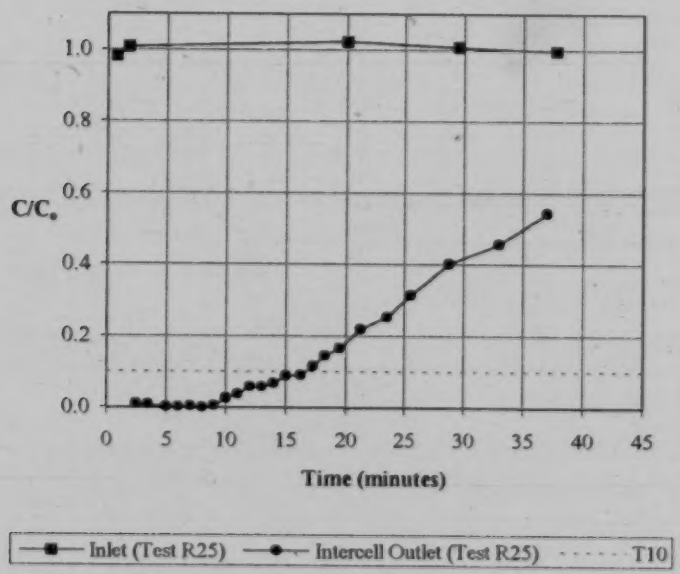

Figure B-21. F-curve for R25 (CR9 + 58.2 L/min + 239 mm)

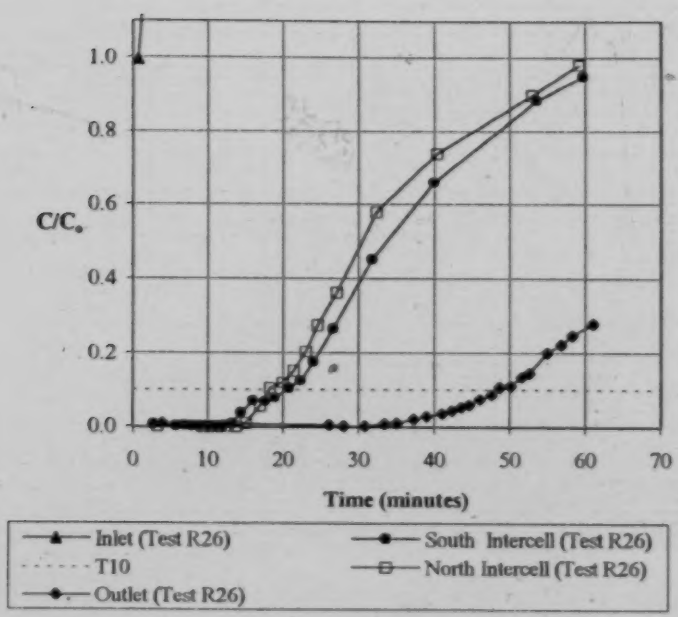

Figure B-22. F-curve for R26 (CR10 + 58.2 L/min + 239 mm)

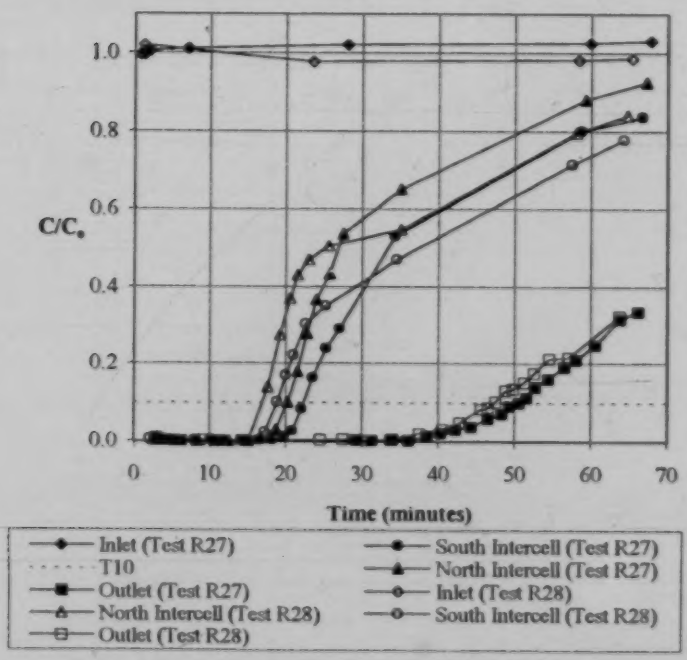

Figure B-23. F-curves for R27 and R28 (CR11 + 58.2 L/min + 239 mm)

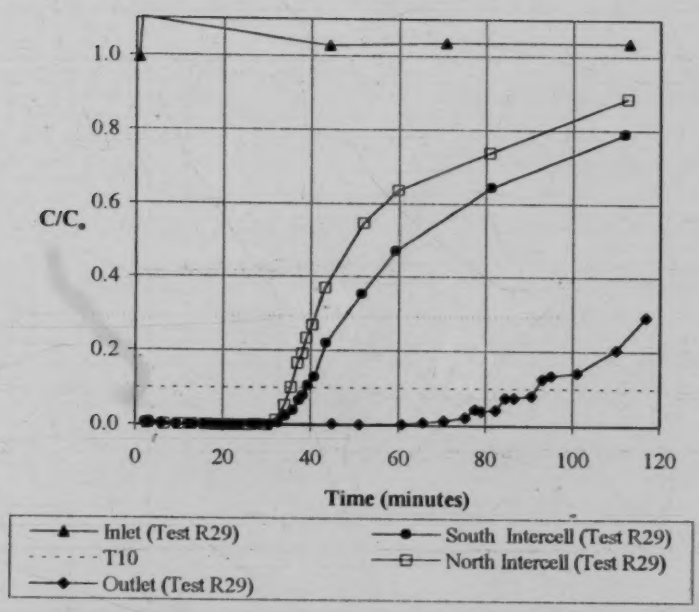

Figure B-24. F-curve for R29 (CR11 + 29.1 L/min + 239 mm)

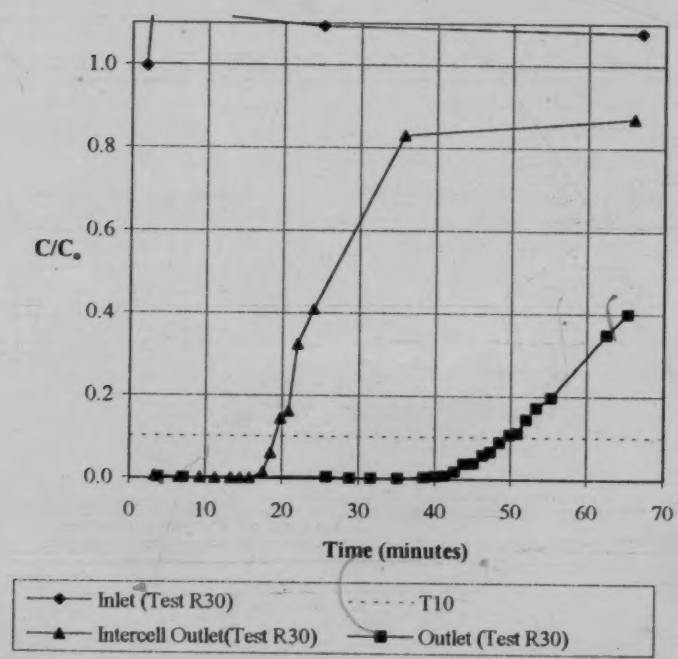

Figure B-25. F-curve for R30 (CR12 + 58.2 L/min + 239 mm)

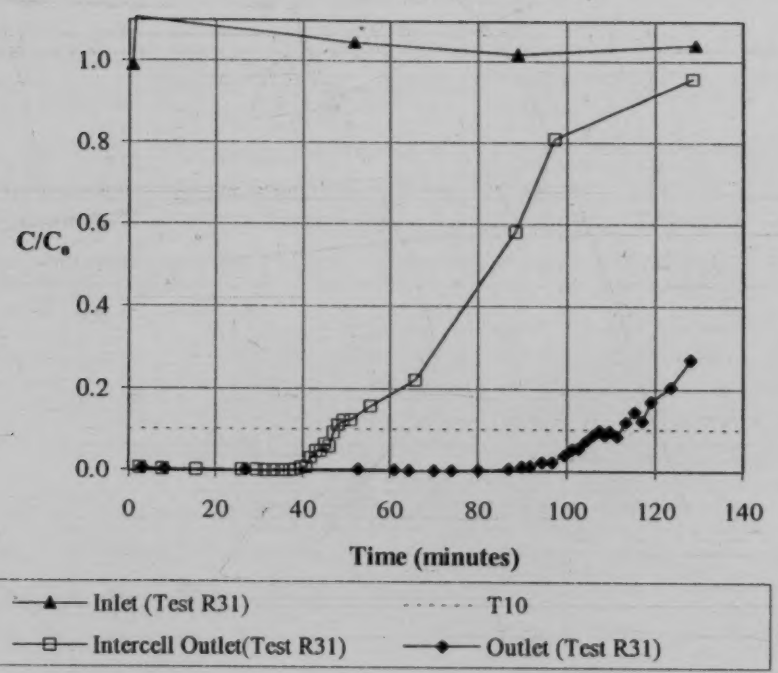

Figure B-26. F-curve for R31 (CR12 + 29,1 L/min + 239 mm)

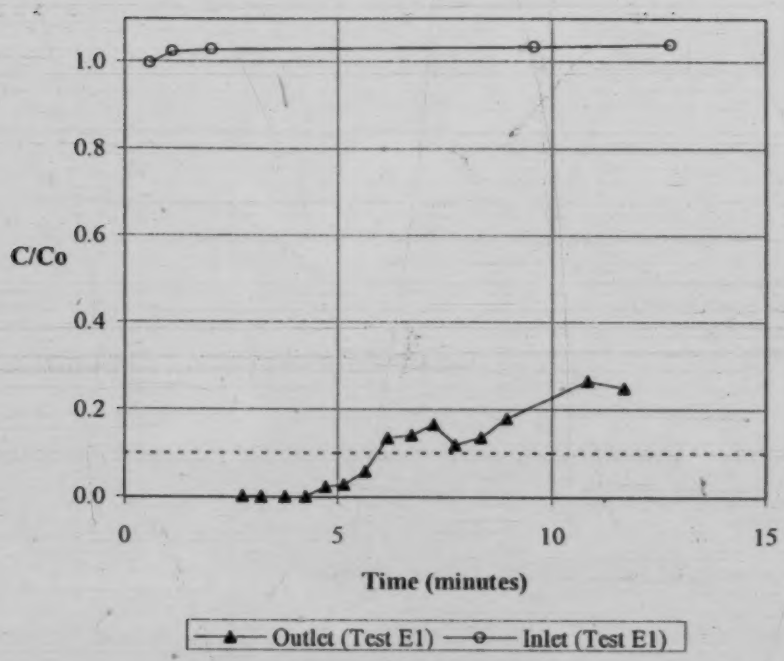

Figure B-27. F-curves for E1 (CE1+11.2L/min+89mm)

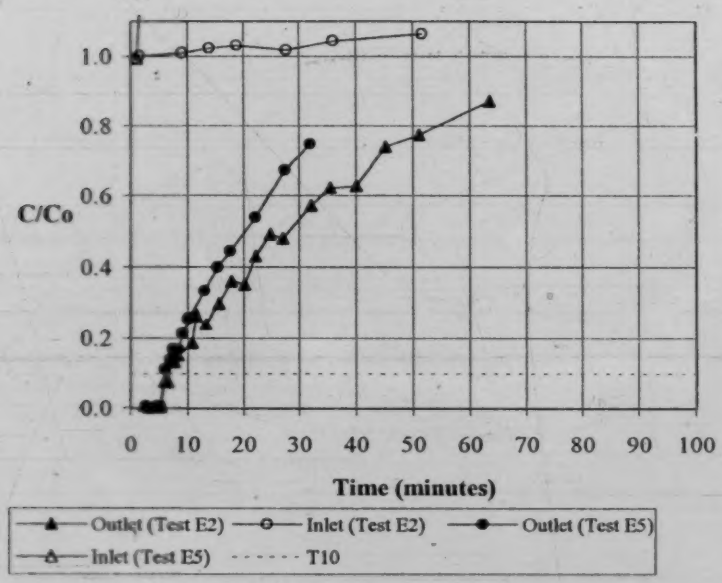

Figure B-28. F-curves for E2 and E5 (CE1+10.3L/min+82mm)

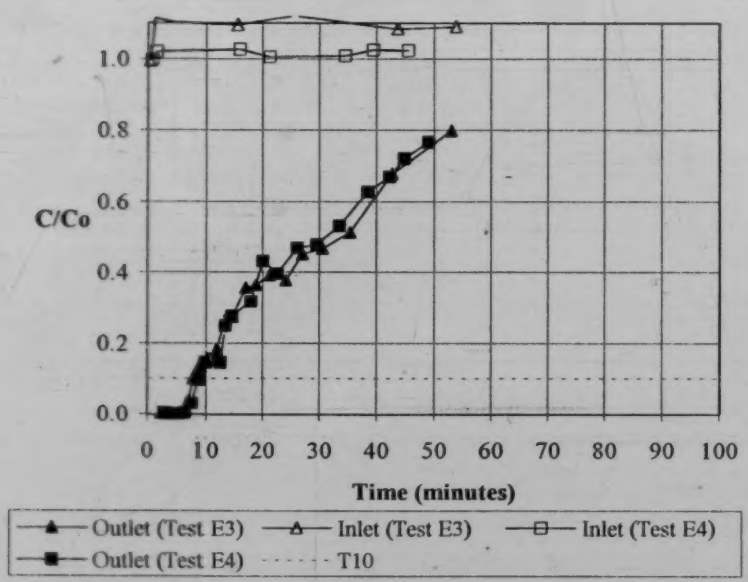

Figure B-29. F-curves for E3 and E4 (CE1+8.1L/min+86mm)

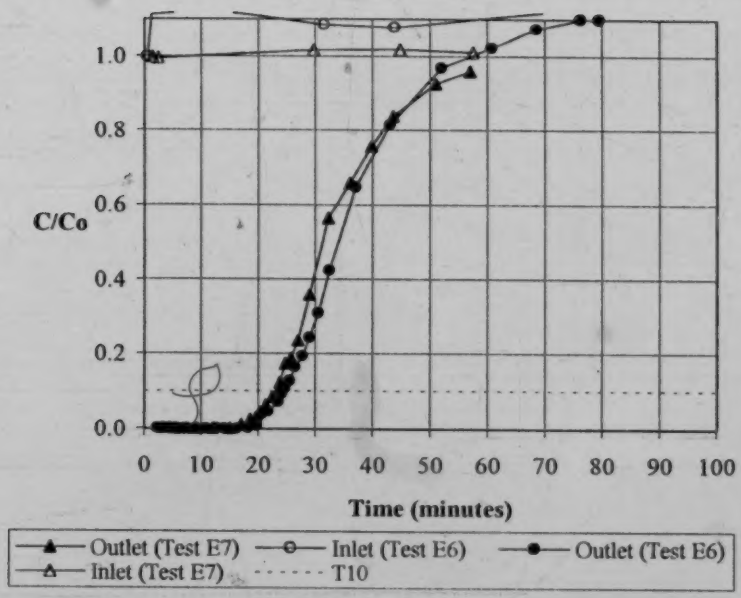

Figure B-30. F-curves for E6 and E7 (CE2+10.3L/min+82mm)

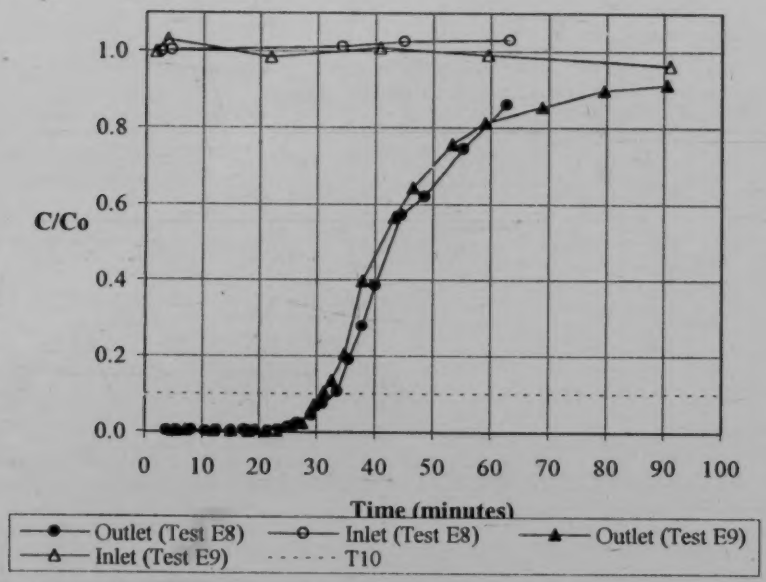

Figure B-31. F-curves for E8 and E9 (CE2+8.1L/min+86mm)

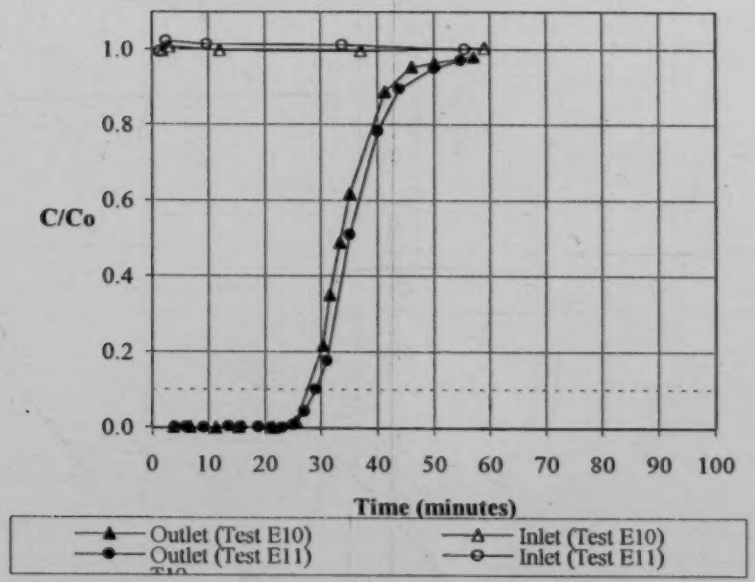

Figure B-32. F-curves for E10 and E11 (CE3+10.3L/min+82mm)

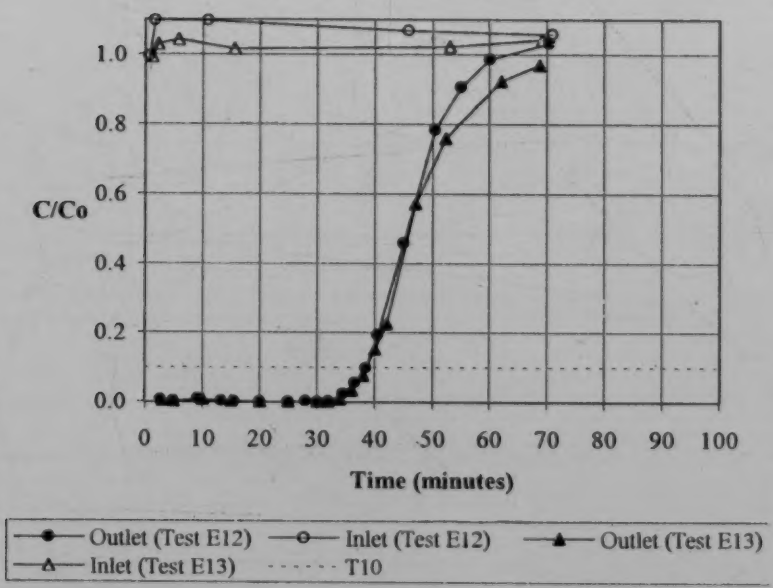

Figure B-33. F-curves for E12 and E13 (CE3+8.1L/min+86mm)